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ENGINEERING DESIGN
HANDBOOK

ROTATIONAL MOLDING

OF

PLASTIC POWDERS

HEADQUARTERS, U S ARMY MATERIEL COMMAND   **APRIL 1975**

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ENGINEERING DESIGN HANDBOOK
ROTATIONAL MOLDING OF PLASTIC POWDERS

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LIST OF SYMBOLS

a = particle radius, cm

b' = experimental constant

Bi = Biot number, hL/k_m, dimensionless

c = mold specific heat, Btu/lb-°F

c_{ps} = polymer specific heat, Btu/lb-°F

g = acceleration due to gravity; ft/sec², cm/sec²

h = heat transfer coefficient, Btu/ft²-hr-°F

k = thermal conductivity, Btu/ft²-hr-(°F/ft)

k_s = polymer thermal conductivity, Btu/ft²-hr-(°F/ft)

K = $2[6Z/Bi)]^{1/2}$, dimensionless

$K(T)$ = function of temperature

L = wall thickness, ft

L_c = chord length, cm

Q = dimensionless flux

r = instantaneous void radius, cm

r = surface roughness factor, dimensionless

r_o = initial void radius, cm

R = cylinder radius, cm

R = characteristic dimension of powder, length

R'_a = bulk rate of cooling

R_s = surface rate of cooling

t = time; sec, min, hr

t_c = total time powder is in contact with mold surface, min

LIST OF SYMBOLS (Cont'd)

t_m = time of powder free fall, min

t_1 = time of initial powder contact with mold, min

t_2 = time of powder release from mold surface, min

T = mold temperature, °F

T_f = freezing temperature, °F

T_L = liquid temperature, °F

T_M = melt or tacky temperature of powder, °F

T_P = powder temperature, °F

T_s = mold surface temperature, °F

T_∞ = oven set temperature, °F

T^* = initial mold temperature, °F

x = distance from the initial powder contact with the mold surface, ft

x = web thickness during sintering, cm

$\overline{z}$ = linear distance into capillary, cm

Z = α_s/α_m, dimensionless

α = thermal diffusivity, ft²/hr

α_{eff} = effective powder thermal diffusivity, ft²/hr

α_m = mold surface diffusivity, ft²/hr

α_s = thermal diffusivity at surface, ft²/hr

β = time constant of mold, min⁻¹

β_1 = dynamic angle of repose, rad

LIST OF SYMBOLS (Cont'd)

γ = surface tension, dyne/cm

γ_c = critical surface tension of solid, dyne/cm

γ_{LV^o} = liquid-vapor interface

γ_{SL} = solid-liquid interface

γ_{SV^o} = solid-vapor interface

δ = thermal penetration thickness, ft

δ = fluid film thickness, cm

δ' = dimensionless penetration thickness

η = viscosity, poise

θ = contact angle between drop of liquid and plane solid surface, deg

θ' = apparent contact angle, deg

ν = mold time constant, min^{-1}

ρ = density, lb/ft^3

ρ_s = polymer density, lb/ft^3

τ = retardation time, sec

τ_w = shear stress at wall, $dyne/cm^2$

υ = volume, $(length)^3$

X_f = movement of freezing front, ft

χ' = dimensionless movement of freezing front

PREFACE

The Engineering Design Handbook Series of the US Army Materiel Command is a coordinated group of handbooks containing basic information and fundamental data useful in the design and development of Army materiel and systems. The handbooks are prepared for the special use of the design engineers and scientific personnel in the Government and industry engaged in the design, development, and upgrading of Army equipment, materiel, components, and techniques.

The present handbook is the first in a series dealing with the technology of plastics. The series will include groups of handbooks on materials, fabrication, and design. This handbook is in the fabrication group. The three handbooks to follow will cover short-fiber reinforced molding compounds, both thermoset and thermoplastic, and joining of resin-bonded advanced composites.

The text of this handbook was prepared by Mrs. Joan Titus of the Plastics Technical Evaluation Center (PLASTEC), the Defense Department's specialized information center on plastics located at Picatinny Arsenal, Dover, New Jersey.

The Engineering Design Handbooks fall into two basic categories, those approved for release and sale, and those classified for security reasons. The US Army Materiel Command policy is to release these Engineering Design Handbooks in accordance with current DOD Directive 7230.7, dated 18 September 1973. All unclassified Handbooks can be obtained from the National Technical Information Service (NTIS). Procedures for acquiring these Handbooks follow:

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CHAPTER 1

INTRODUCTION

1-1 DEFINITION

Rotational molding, rotomolding, or roto-casting is a production process to form hollow parts of limitless size wherein liquid or powdered thermoplastic resins—and to a limited extent thermosetting materials—are charged into a split mold. The mold is then rotated continuously in a biaxial mode, in a high-temperature environment to above the resin melt temperature. When the plastic material has covered the inside of the mold and densified, the mold assembly while still rotating is cooled to room temperature. The rotation is stopped and the part removed.

1-2 BACKGROUND

Rotational molding is not a new processing technique, having had a place in industry since the 1940's. The materials prior to 1961 were limited to vinyl plastisols in liquid form and were used primarily in the manufacture of novelties and decorative items such as artificial fruits, mannequins, children's toys, and hollow display items.

What is new in rotational molding in recent years relates not to plastisols but to powdered resins of about 35 mesh which have triggered improvements in equipment design and the overall technology, making this technique among the major plastics processing methods of today. Therefore, this handbook will be devoted to the thermoplastic powdered engineering grade polymer rotational molding technology and not to plastisols which have little significance in the military complex.

1-3 MATERIALS

In 1961, the first polyolefin powder, a low-density polyethylene, was publicly demonstrated to the rotational molding industry. Indications are that polyethylenes will remain one of the most popular materials for roto-molding, because of their processability, broad range of properties, and low cost. Today, however, most of the major thermoplastic raw material suppliers have investigated specially formulated powders for rotational molding. These include impact styrene, polypropylene, nylons, acrylonitrile butadiene styrene, polycarbonate, acetals, ionomers, fluoropolymers, polybutylene, rigid polyvinyl chloride, and special grades of the cellulosics. They can be foamed or reinforced with fiberglass. In addition to the raw material suppliers, many rotational molders also have used custom grinding services or have their own in-plant grinding facilities, which also enlarges the material selection for this process.

The commercial supply of rotational molding powders has been curtailed recently. The petroleum shortage commencing in 1973 with ensuing feed stock allocations to resin manufacturers and resin price controls resulted in plastic shortages. The manufacture of molding powders especially was affected since powders cost about $0.06 per lb more than pellets (due to the grinding operation required) and the fact that rotational molding accounts for only about 2 percent of the plastic processors' operations.

1-4 ROTATIONAL MOLDING PROCESS

The six basic steps associated with rotational molding, namely:

1. *Charging*. Charging the molds with a predetermined weight of powder desired in

the end product.

2. *Clamping*. Clamping mold parts in place. The entire mold is made of heat-conductive material for totally enclosed pieces. When one or both ends of the pieces are to be open, heat-insulating covers are used to close the mold.

3. *Heating*. The charged molds are heated while simultaneously rotating around two axes in planes at right angles to each other. Heating can be accomplished in hot air convection ovens, molten hot salts spray, circulating oils, open flame, and infrared ovens. The introduction of an inert gas such as nitrogen into the mold during the heating cycle is sometimes performed to flush out the oxygen and thus prevents oxidative degradation of the resin while it is being fused. Molds usually are vented to prevent pressure build-up.

4. *Rotation*. The biaxial rotation results in the powder being evenly distributed to form hollow objects with uniform walls when the resin fuses except where heat-insulating covers are used.

5. *Cooling*. When all of the powder has been fused into a homogeneous layer on the walls of the mold, the mold is cooled usually by air and/or water spray while still being biaxially rotated.

6. *Part Removal*. The mold is opened and the end product removed. Removal is usually manual and simplified by use of a release agent.

1-5 EQUIPMENT AND TOOLING

The mold-handling system includes all the equipment required to transport the mold(s) through the loading, heating, cooling, and unloading steps and to bring about the biaxial rotation of rotational molding. The main parts of the system are the spindle, spider or mold mount, and the drive mechanisms. There are basically four types of handling machines in use. They are fixed-spindle, sin-

gle- and multiple spindles, shuttle, and jacketed or ovenless molds. Specific information is contained in Chapter 3.

Rotational molds are generally made from cast aluminum, 10-20 gage sheet steel, beryllium-copper (Be/Cu), or electroformed copper-nickel. Split molds are required for part removal. Flanges may be tongue and groove, interlocking or flat with locating pins. Venting of molds is recommended to maintain atmospheric pressure inside the closed mold during the entire molding cycle. Mold wall thickness will be determined by the type of equipment used for rotational molding. Molds used in a hot-liquid machine should have a greater wall thickness than those used in an air-convection oven — normally 0.5 in. and 0.25 in., respectively, for cast aluminum.

1-6 ROTATIONAL MOLDING CRITERIA

The general criteria for selecting the rotational molding process are:

1. Fabrication of hollow items having large surface areas which would require extensive tool design and complicated molds.

2. Fabrication of hollow items having complex shapes such as convoluted wall sections, undercuts, or similar irregularities that would make difficult tool design as well as production problems.

3. The manufacture of relatively large items subjected to widely varying production schedules such as those keyed to seasonal cycles or uncertain contracts.

4. When the total production volume would be at a level that would prohibit sizable investment in expensive tooling.

5. When the item is subject to unpredictable changes in styling, or when a quick styling change could be exploited profitably in the market.

6. When identical items or different parts of an item are required in different colors.

1-7 ADVANTAGES AND DISADVANTAGES OF ROTATIONAL MOLDING PROCESS

1-7.1 ADVANTAGES

Some of the outstanding advantages of rotational molding are:

1. Products can be made seamless and virtually strain free with little or no waste scrap.

2. Wall thickness can be uniform to about ±0.015 in.

3. Intimate detail, various textures, or high gloss are easily obtained.

4. Molds are simple, inexpensive, and can be fabricated with a short lead time.

5. Process is well suited for the production of very large or totally enclosed parts.

6. Prototype molds can be manufactured for experimental purposes without great expense.

7. Double-wall constructions are feasible.

8. Metal inserts often can be molded as integral parts of the item.

9. Molds can be designed with little draft.

1-7.2 DISADVANTAGES

The main disadvantages are:

1. Rotational molding materials are quite limited.

2. Molding cycles are longer than injection or blow molding.

3. Labor is intensive due to manual loading and unloading of molds.

4. Bosses cannot be molded.

1-8 APPLICATIONS

Rotational molding has been used successfully in a wide variety of applications; some examples are portable lavatories, 15-foot boats, containers, pallets, incendiary bomb casings, missile containers, storage tanks, automobile fender liners, and battery cases.

CHAPTER 2

ROTATIONAL MOLDS

2-1 GENERAL

The selection of rotational molds depends upon the size, shape, complexity and surface finish of the part to be molded; resin compound; molding cycle time; quantity of molds required; and production volume. Molds should be as thin-walled and lightweight as practical.

2-2 MOLD MATERIALS

There is a wide choice of mold materials for rotational molding. They are stainless steel, 10-20 gage sheet steel, cast and fabricated aluminum, cast and machined nickel, electroformed chrome plated nickel and nickel-copper, and cast and machined Be/Cu. The thermal conductivities of these materials are given in Table 2-1.

There are also some high strength aluminum alloys. These alloys are very susceptible to a hard coating process. The coating is not a plating; it does not chip or peel off. The surface of the aluminum is converted into aluminum oxide which is extremely hard. The surface has to be polished if a smooth finish is desired. It is possible to mask off the cavities

TABLE 2-1

THERMAL CONDUCTIVITIES OF THE METALS FOR ROTATIONAL MOLDS

METALS	THERMAL CONDUCTIVITIES[1], Btu/ft^2-hr-($^\circ$F/ft) at 572°F
Steel	25
Aluminum	133
Copper	212
Nickel	32

and to hard coat any portion, such as the parting lines. The cavities should be heat treated, machined, then, if desired, hard coated.

Another aluminum treating process (Tufram®) provides a steel-hard surface combined with locked in permanent release properties[2]*.

Other mold materials such as porous metallic or ceramic have been impregnated with polytetrafluoroethylene to produce superior nonstick characteristics. However, they are not recommended for molding resins that require oven temperatures above 500°F.

2-2.1 SUGGESTED USES

Aluminum or electroformed nickel-copper alloys are recommended for small or intermediate-sized molds, complex shapes, and when several molds of one design are required. Steel is used for most large molds and for a prototype mold of a single design because it is the most economical material. Cast Be/Cu is used where fast molding cycles and superior chemical resistance are required. If overall cycle time is not important but high surface gloss is, chrome-plated stainless steel is recommended. Cast aluminum molds are suitable for any configuration since they generally do not cause wall thickness problems and allow a textured finish if desired. One problem does exist, however, with aluminum molds—porosity. Molds that have been cast in plaster usually have smoother, less porous surface than those cast in sand.

Good quality, porosity-free molds with

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*Superscript numbers refer to References at the end of the chapter.

(A) Flat   (B) Offset   (C) Tongue-and-groove

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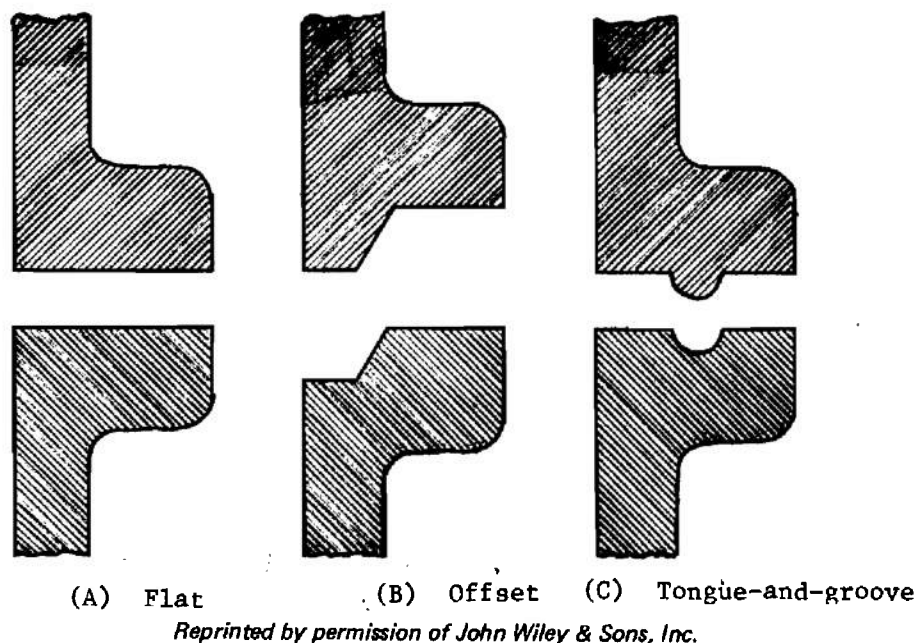
Figure 2-1. Three Types of Flange Mating Surfaces for Rotational Molds[3]

properly designed parting lines are essential to successfully mold an item. Normally, properly welded, fabricated steel or aluminum, electroformed, or machined molds are porosity-free.

2-2.2 MOLD LIFE

Mold life is shorter for rotational molding than for injection or blow molding, since the exteriors of these molds and their mounting assemblies are exposed to severe thermal shock during the molding cycle. This results in crystallization of the metal. Proper mounting also is required or molds will warp.

2-3 MOLD DESIGN

2-3.1 SPLIT MOLDS

Rotational molds for other than plastisols should be of a split design so that the opening coincides with the largest dimension of the part. At least the opening must be large enough so that the item can be removed without distortion.

2-3.2 WALL THICKNESSES

The type of equipment used for rotational molding will determine the mold thickness. Molds utilizing a hot-liquid (oil) or those used in a hot-molding salt-spray machine should have greater wall thicknesses (about 5/16 to 1/2 in.) than those used in a hot-air convection oven (3/16 to 1/4 in.). Thicker mold walls permit the high temperatures caused by the fast heat transfer of the liquid to heat the powder uniformly without causing hot spots and with less risk of mold warpage. Thinner mold walls result in a reduction of cycle time in a hot air convection oven.

When infrared mold heating is used, wall thickness may be controlled by painting. Dark paints on the outer mold surface result in higher heat absorption and consequently in thicker part walls. Light-colored paints, or aluminum paint, reflect the heat and result in thinner walls. Paints used for this purpose must be thermally stable at the high oven temperatures used. Paints have a relatively small effect on wall thickness compared with insulating covers made of materials such as asbestos.

In addition, the wall thickness in a specified area may be reduced by the application of an insulating material, usually asbestos, to
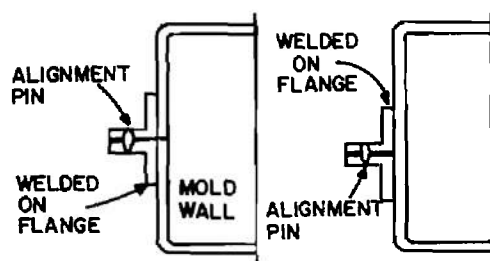
*Figure 2-2. Proven Mold Parting
Line Designs*[4]

the outside of the mold resulting in a less resin fusion.

Some representative mold wall thicknesses for hot air convection ovens are:

1. Aluminum. 2/8 to 3/8 in.

2. Steel. 3/64 to 1/8 in.

3. Be/Cu. 1/16 to 3/8 in.

4. Nickel/copper. 5/64 to 5/32 in.

2-3.3 OPENINGS

When openings are required in the molded part, mold insulating lids or inserts are used in the place of metal in the open areas. Usually asbestos boards, Teflon®, or silicone foams are used.

2-3.4 FLANGE MATING SURFACES, PARTING LINES, AND HINGES

There are three main types of flange mating surfaces for rotational molds, namely: flat, offset, and tongue-and-groove. These are illustrated in Fig. 2-1.

2-3.4.1 MATING SURFACES

A brief discussion relative to the application of mating surfaces follows:

1. Flat. The flat-type can be used on either

hot-air convection-oven or hot-liquid machines. It simplifies mold maintenance, but has a higher initial cost than either the offset or tongue-and-groove surface. The mating surfaces should be machined smooth for a good fit, and the molds should be stress-relieved before the parting lines are matched.

2. Tongue and Groove. The tongue-and-groove flange is recommended for use with the hot-liquid machines since it is more difficult for the liquid to penetrate that distance to the cavity.

2-3.4.2 PARTING LINES

The parting line design and certain types of inserts should be given special consideration. The parting line should be designed to seat on the inside surface and should be relieved to the outside. This prevents water or vapor from being trapped in the parting line. As the temperature of the mold is increased, trapped moisture or vapor can expand and blow through the part or enter the wall and form a bubble. The same basic principles should be used for inserts that are seated on the mold. The insert should seat on its outer edge and be tapered to the center. Two types of parting line designs that have been successfully used are shown in Fig. 2-2.

For a moderately curved parting line, the offset or tongue-and-groove register can be used. When the curved parting line becomes extreme, the best register is the offset. The tongue-and-groove can bind and not open and close properly. If there is any choice as to where the parting line should be, the rule is the straighter the line, the better the design.

In certain cases, as shown in Fig. 2-3, two objects are molded together. These are then separated on the designed parting line or lines.

2-3.5 MOLD MOUNTING AND CLAMPING

Mounting bosses should be located around the periphery of the parting line, perpendicular to its plane, and steel rods should be fitted into them. If long mounted aluminum bosses
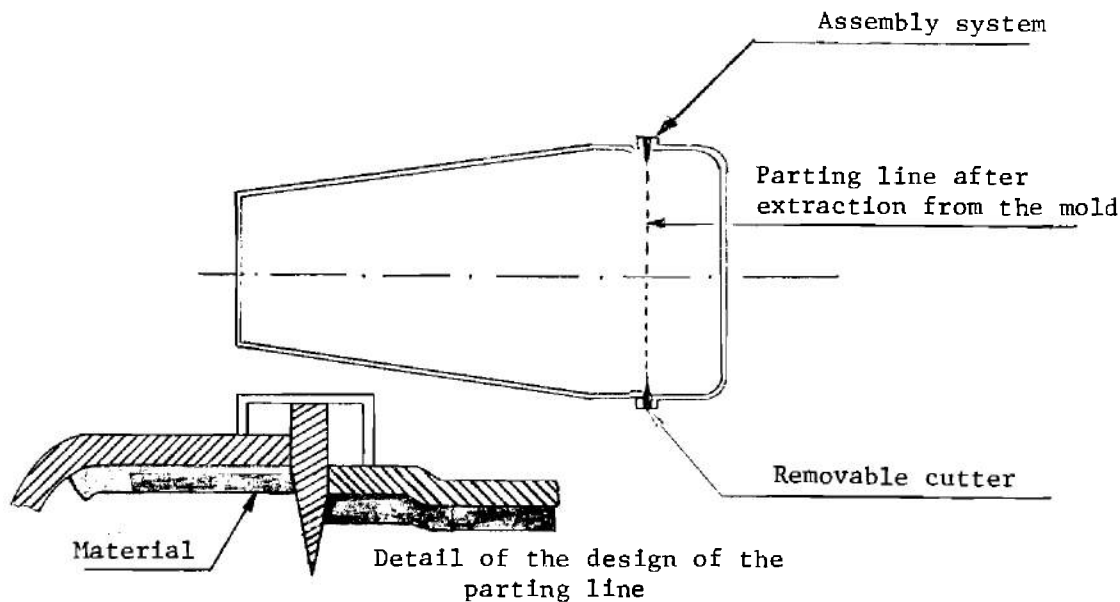
Figure 2-3. Two-part Mold [5]

were used, they would rob the heat. Also the metal compresses and in a short time the cavity is not closing properly.

Molds should be mounted on a steel frame welded together and designed to receive the mounting bosses of the cavities. These frames are referred to as spiders. Some machines use square spiders and some round, but the most important consideration is that they be made of steel. Channel iron, square steel tubes, or 0.25-in. flat hot roll steel are some of the materials used for spiders. The square tubing and the 0.25-in flat stock can be rolled into concentric circles to make round spiders.

The dimensions of the steel depend upon the size of the spider and the closing pressure needed to keep the cavities together. After the spiders are welded together they should be normalized before machining.

Spiders can be designed with just a few simple hold-down bolts allowing the cavities to do all the registration to very complex mechanisms with springs, worm drives, or air cylinders for opening and closing the mold. How elaborate the spider design becomes depends on the situation. Also, heat distribution has to be balanced with a spider arrange-

ment that allows a practical unload-load cycle time.

Production length will be a major influence in the design. Two important features to be considered are opening and closing the mold in a straight line perpendicular to the parting line, and the use of guide pins to keep the parting lines from smashing.

Figs. 2-4, 2-5, and 2-6 show several clamping designs.

The two ways of mounting molds in the spindle are double centerline and offset arm as illustrated in Fig. 2-7. The most common method is to attach the mold(s) to the spiders lying directly above and below the spindle double centerline mounting. This mounting is preferred for the production of small items because it permits easier mold loading and unloading. For large items, the so-called offset arm is preferable. Also, it minimizes variations in wall thickness by bringing the center of volume of the mold close to the intersection of the major and minor axes of rotation. A wide difference in peripheral velocity from top to bottom, caused by a greatly offset mold, may result in poor material distribution and nonuniform wall thickness of the moldings.

Movable part

Fixed part

Quick-action bolt

Locking ensured by the framework
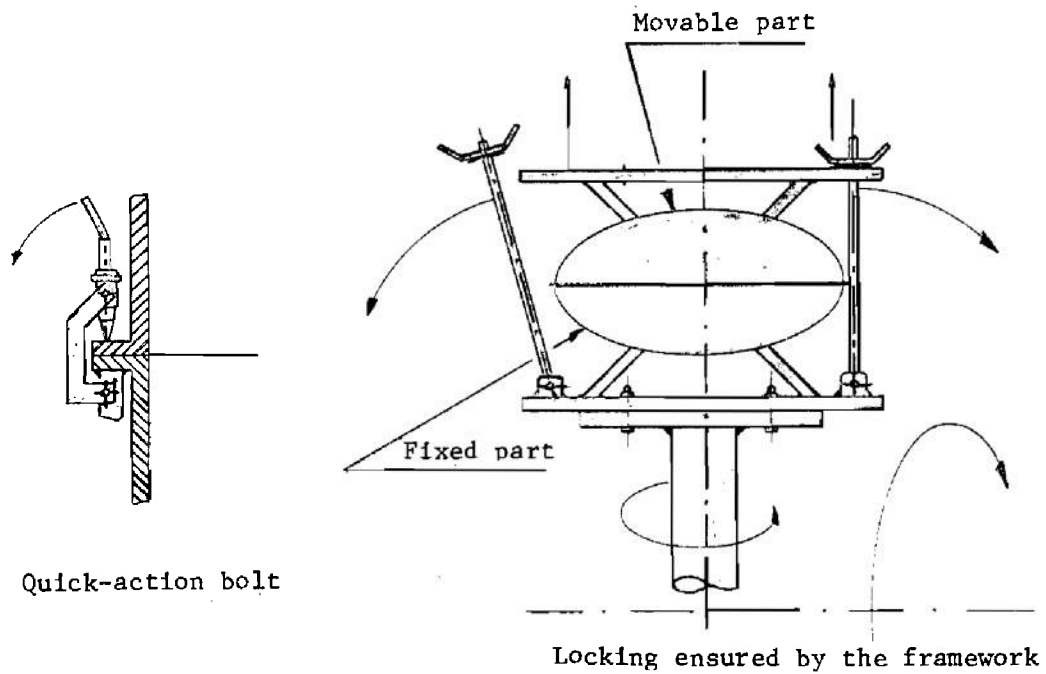
Figure 2-4. Mold Clamping[5]

LATCH
TYPE CLAMP

MOLD STAND-OFF
SPRING

BOLT

MOLD FRAME

CAST
ALUMINUM
MOLD

MOLD FRAME
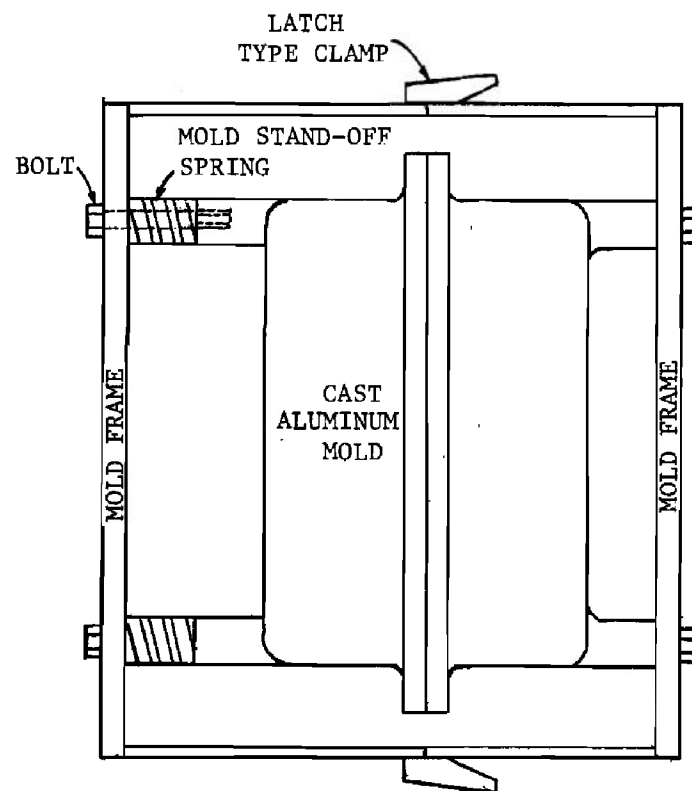
Figure 2-5. Spring Loaded Parting Line for Cast Aluminum Mold[6]
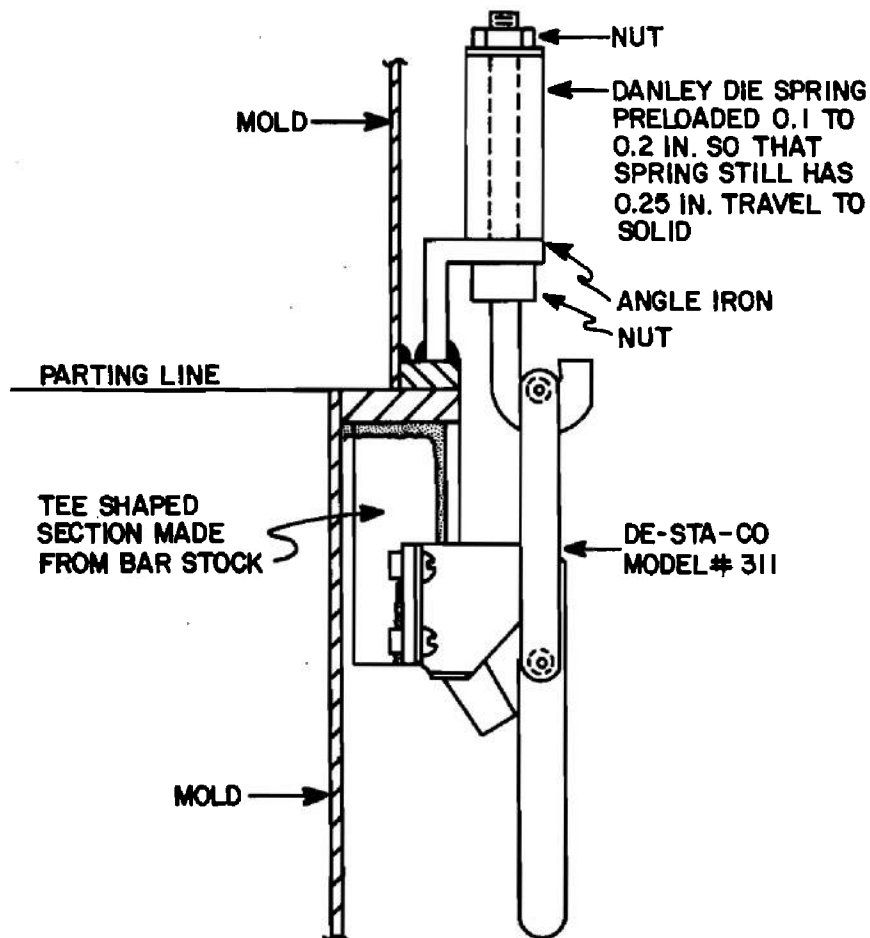
Figure 2-6. Spring Loaded Parting Line for Fabricated Steel Mold [6]

(A) Offset-arm   (B) Double centerline
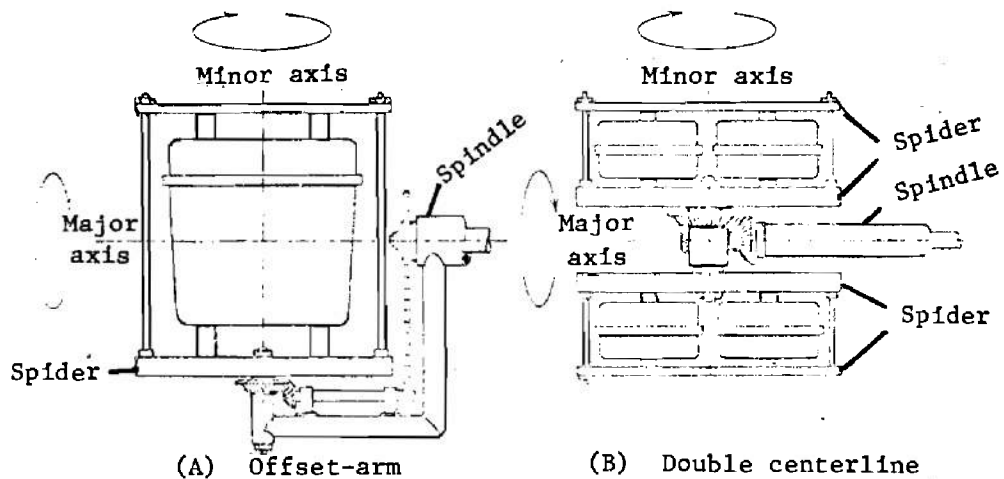
Figure 2-7. Mold-mounting Systems
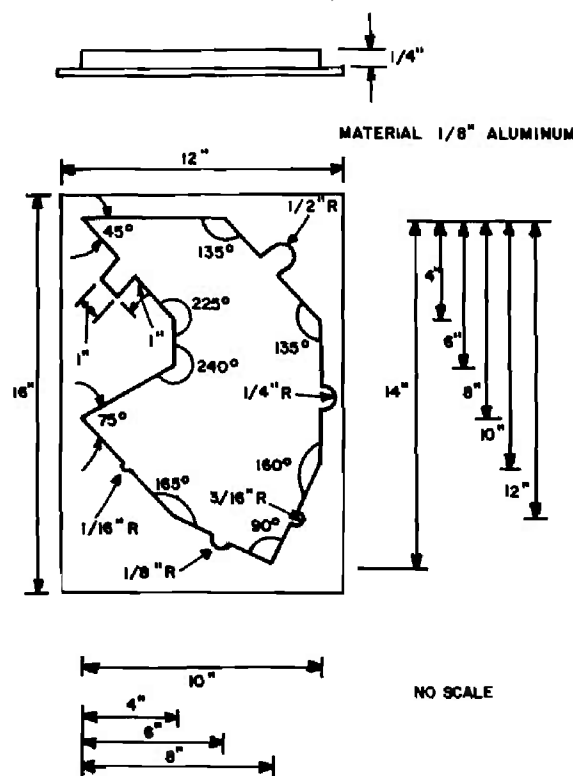
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Figure 2-8. Mold for Angles and Radii of Curvature[1]

2-3.6 CORNER RADII

Rao and Throne experimented with the aluminum corner mold shown in Fig. 2-8. Corner angles of 45, 75, 90, 135, 165, 180, 225, and 240 deg were included in this mold together with a 1 X 1 in. square section, and indentations with radii of 1/16, 1/8, 3/16, 1/4, and 1/2 in. Rotational molding with many plastics in this mold has shown that rarely will the 45- and 75-deg and 1/16- and 1/8-in. test areas be free of voids. For materials such as impact styrene or ABS, even 90-deg, 135-deg, and 3/16-in. test areas were incompletely filled. The square section was rarely filled, regardless of the material used. Based on this testing it is concluded that, for most materials, mold radii of 3/16 in. and parting lines placed on 180-deg walls are the safe lower limits for avoidance of voids in part surfaces[1].

2-3.7 FLAT PANELS

Flat panels should be avoided because they will shrink away from the mold as they cool, especially if they are cooled too rapidly with consequent warpage and brittleness.

2-3.8 CORE SECTIONS, RIBS, AND HANDLES

Core sections can be made. Deep ribs, kissed off, and handle areas should be designed with a greater taper than normal for easy part removal. A 6- to 8-deg taper is recommended for crosslinked polyethylene[4]. Deep handle core sections and other deep core sections that kiss-off from one side of the mold to the other should have an opening for hot air passage through the mold as illustrated in Fig. 2-9. This will help prevent thinning due to air being static in the bottom of the core section.

2-7

AIR FLOW
BUFFETED

(A) Cross Section--Poor Design

AIR FLOW

(B) Cross Section--Good Design
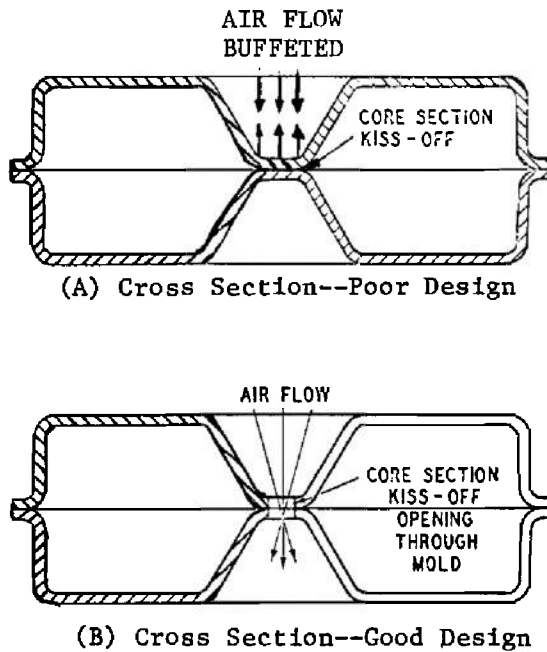
*Figure 2-9. Mold Design With Kiss-off
Section or HandleSection [6]*

One of the most disastrous errors made by
end-users considering rotational molding for
the first time is the design and fabrication of
prototype tooling without pretesting mold
features such as closure, angles of radius, and
overall variation in part thickness. This can be
done by running experiments on simple molds
such as ball, cylinder, and disks molds on a
rotational molding machine prior to design
and fabrication of prototype or production
tooling.

2-3.9 VENTS

Molds should be vented from the cavities to
maintain internal atmospheric pressure during
the molding cycle. Venting results in less
flash, less distortion of the part, thinner mold
walls, less pressure needed to keep the mold
closed, and longer mold life. It will also
prevent blowouts caused by pressure during
heating and/or part collapse or imperfections
resulting from any vacuum created during the
cooling cycle.

The vent is a thin-walled metal or Teflon®
tube which extends to near the center of the
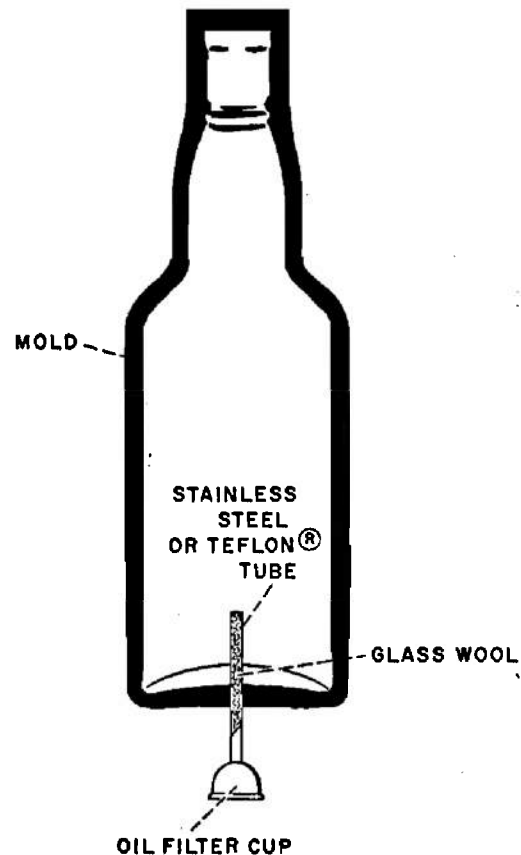
*Figure 2-10. Schematic of a Vented Rotational
Mold for a Display Bottle. [7]*

mold. It must enter the mold at a point where
the opening that it will leave will not harm
the appearance or utility of the molded item.
The vent is filled with a material, such as glass
or steel wool, to keep the powder charge from
entering the vent during rotation. The end of
the vent outside the mold must be protected
so that no water will enter during cooling, or
so that hot liquid if used will not enter during
heating. Sometimes an oil filter cup or metal
cup is used for this purpose. Some designs are
shown in Figs. 2-10 and 2-11.

2-4 MOLD FABRICATION

2-4.1 FABRICATED MOLDS

These molds are made by convention-
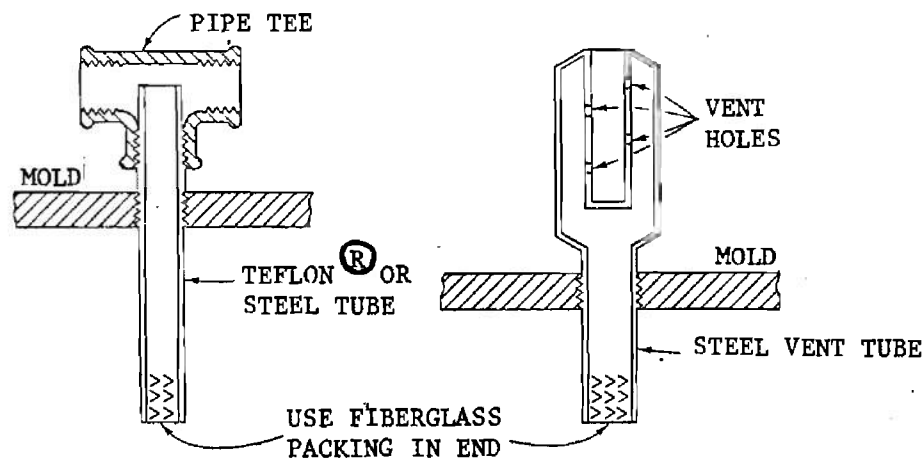
Figure 2-11. Two Methods To Reduce the Water Vapor Entering Vent Tube During Cooling[6]

al methods such as spinning, turning, and forming and are welded together to make the finished shape. This form of mold can give fairly long production runs at a very reasonable price, depending upon intricacy. They are made from sheet steel, copper, and aluminum.

With steel and aluminum fabricated molds, improper welding can cause porosity in the weld. To obtain good porosity-free welds three simple steps should be taken:

1. The welding rod must have a similar thermal coefficient of expansion as the material used in the mold.

2. The inside should be welded first to get good penetration.

3. Grind or grit blast the back of the first pass before the second pass is made. This procedure should be followed for each additional pass. This method helps to eliminate any porosity that might be caused by oxides formed on the previous pass.

2-4.2 CUT MOLDS

A cut mold is one machined from wrought stock. Under this heading we find steel, stainless steel, Be/Cu, and aluminum. The first step is to produce from the print which will have included plastic shrinkage an exact pat-

tern of the finished part. The materials for this pattern can be just about any formable substance such as plastics, plasters, woods, clays, and aluminum.

From this pattern a female impression is cast in either epoxy or high-strength plaster. This impression is then placed on a duplicator or tracing machine, and cavities are produced in the premachined blocks. This method produces a very accurate mold capable of producing a large number of finished parts.

Machined cavities of aluminum and Be/Cu fall into the same class as pressure-cast aluminum and Be/Cu. Only the steel hob is eliminated. Molds made by this method have a better and more uniform density than that found in pressure-cast and ceramic casting.

2-4.3 CAST MOLDS

Molds can be cast by two methods: pressure and gravity. The materials used are steel, Be/Cu, and aluminum.

2-4.3.1 PRESSURE CASTING

Pressure castings are produced by pouring molten metal over a steel hob and applying pressure. The metal flows to conform very precisely to the shape and surface finish of the hob. In making the hob, allowance must be made for the metal shrinkage (approxi-

2-9

mately 0.005 to 0.007 in./in.) as well as a sufficient draft angle of at least 1.5 deg for removal.

Air hardening tool steels are generally best for hobs. These metals machine readily, do not shrink excessively when hardened, and provide the necessary hardness and strength. Generally SAE H-12 or SAE H-13 are used for making hobs. When available, SAE H-23 (oil-hardened) is one of the better grade steels to use where a large number of cavities are required from a single hob. Under certain circumstances it is possible to use a prehardened steel. The safest thing is to check with the caster before proceeding with cutting the hob.

The hob base requirements also will vary with the conformation of the impression. Therefore, it is advisable to contact the pressure caster for the proper dimensions. Ordinarily, pressure castings can be made up to 200 lb in weight, the limit being determined by the shape of the piece.

Control of the melting and pouring temperatures of the molten metal is important. Overheating is particularly harmful. It is also recommended to minimize turbulence during pouring.

In pressure casting the mold, the hob should be thoroughly cleaned and covered with a parting agent. The hob, shim plates, and top pusher plate are heated (from approximately 800° to about 1150°F). When heated, the chase or mold casing around the hob assembly is lowered and moved onto a hydraulic press. The molten metal is poured at the recommended temperature into the chase so that it first contacts the chase walls and then flows onto the hob. A deflector will insure this pattern of flow. When the molten metal has covered the hob, the pusher plate is placed over the molten metal and press force applied immediately. Because the molten metal will begin to solidify when it contacts the chase and hob, time and pressure are both important.

After pressurizing the chase is raised and the side or shim and pusher plates loosened by rapping them. It is important to remove the hob from the mold before too much cooling occurs. If cooling proceeds too far, it will be necessary to heat the hob and mold to facilitate separating them.

Pressure casting requires a two-stage type hydraulic press to allow high speed for approaching the working position and slow speed for pressurizing. Daylight must be large enough to provide working area. Pressure capacity must be between 1000 and 2000 psi, preferably nearer 2000 psi. For a press with a 20-in.^{2} platen, this means a 750-ton press.

Pressure-cast aluminum and Be/Cu molds basically are used when the shape is not of intricate design.

2-4.3.2 GRAVITY CASTING

The other method of casting molds is the "gravity cast" method. There are many different mold mediums used into which the metal is poured. However, all systems are filled by gravitational force only. Atmospheric pressure may be added by the use of risers on the back section, but basically it is gravitational force that fills the molds. This, of course, means the grain is of different size from pressure castings. While this type of casting dates back to ancient times, it is only recently that technical improvements have made its use more widespread in the plastics industry.

2-4.3.2.1 CERAMIC CASTING

Ceramic casting follows any one of a number of patented proprietary procedures. A typical sequence is described in the paragraphs that follow.

A wood pattern of the part to be produced is made with proper shrinkage allowances for metal and the plastic. These shrinkages will vary from piece to piece and it is best to establish them for each piece. Generally, 0.016 to 0.018 in./in. is allowed for metal

shrinkage and 0.005 in./in. for plastic. The moldmaker casts a special, quick-setting liquid rubber around the pattern. The elastic quality allows stripping from the pattern even though the pattern may have a deep-grained surface. It also provides faithful reproduction.

Now a ceramic is cast into the rubber mold, producing a replica of the designed part. A proper ceramic mixture will combine good surface reproduction with relatively high permeability. This last property allows adequate outgassing during casting of the metal around the ceramic, resulting in a sound, dense casting.

After pouring the ceramic slurry into the rubber mold, the moldmaker allows it to solidify and then fires it in an oven. Melting and pouring of the molten metal around the ceramic pattern follows the steps covered under hot hobbing.

After solidification of the metal, the ceramic is broken away. Metal cooling is controlled to achieve good dimensional tolerances in the casting.

Ceramic casting requires a rubber pattern shop, ceramic mixing kettles, and a bake-out oven of the car-bottom or tunnel types for moving large ceramic patterns in and out.

2-4.3.2.2 SAND CASTING

Sand casting is acceptable in some cases. It may be used for large molds if there is no need for fine surface detail, as in a fender underliner for an automobile. Generally CO_2-hardened sand is used. If surface finish is important, the best approach is to use a ceramic face backed up by CO_2-hardened sand. Sand casting equipment is not extensive—CO_2, gas tanks, hose, and a high-speed sand muller.

2-4.3.3 ATTRIBUTES OF CAST MOLDS

Casting molds eliminate a great deal of expense in machine tools. A portable 0.5-in. drill with a sanding wheel or a milling machine are generally used to finish off the external surfaces of molds. A radial drill press will suffice for drilling passages and holes for attachment. An electric discharge machine may be useful in remedying casting defects. A hand snagging wheel will remove stubs.

An enclosure box with a pump, hose, and nozzle make up the facility for liquid honing for finishing molds. If pickling is desired, acid and water tanks, and a small heating system are all that are necessary.

Many types of finish can be duplicated with the casting process—wood grain, leatherette, stippling, cloth, basket weave, etc. With the exception of highly polished surfaces, most finishes are possible.

Some advantages of the gravity cast system are:

1. Highly irregular parting lines can be cast from a model with matching cavities and cores.

2. The castings can be made from models of different materials effecting a savings over machining an expensive hob.

3. Castings can be made by duplicating an existing piece.

4. Undercuts can be cast by using the strippable rubber technique.

5. Cores and cavities can be cast, allowing for plastic-thickness.

6. It is faster and less expensive in many cases to make a model rather than machine a costly steel hob.

7. Less expensive dies can be made for short run items by substituting less costly metals such as aluminum or die metal.

However, close tolerances cannot be maintained on large castings, as the shrinkage rate will vary somewhat because of size or shape of the casting. The only way exact sizes can be maintained in any casting is to make a casting, "mike it up", adjust the pattern, and

make another. Since this is not feasible on large castings, the next best thing is to have the cavity pattern made small, then, if necessary, it can be enlarged by machining the critical areas. At other times it may be necessary to incorporate some flexibility in the design of the item.

2-4.4 ELECTROFORMED MOLDS

Electroforming consists of electroplating against a conductive surface for a long period of time to reproduce a reverse of that surface. Patterns, or mandrels, as they are generally called, may be made of almost any material that does not absorb moisture, or does not expand excessively through a 100-deg F heat differential. Expansion during the first half-hour of plating will crack the very thin electroform. The adhesion of the plating to the mandrel must be strong enough to retain the surface detail and contour, but weak enough to be removed after plating. The adhesion is determined by the film deposited on the pattern or mandrel.

Factors affecting the choice of mandrel material include surface finish requirements, shape, and plating bath composition and temperature. Materials include plastics, glass, wax, latex, rubber, wood, plaster, and most metals except zinc. Metal mandrels are usually nickel, nickel-copper-nickel, or nickel chrome plated. Thickness can be closely controlled. It can be as little as 0.02-in. for pressureless rotational molding. Nickel mold facing is chemical resistant, tough, hard, and can be highly polished. In the nickel-chrome, the chrome acts as an electrical conductor as well as a release agent for the nickel since the electroform face will not adhere permanently to the chrome surface of the mandrel.

Aluminum mandrels must be sealed against acid attack and, therefore, are not used often. Steel, copper, and brass can be used although if any parts of the model are not to be electroformed, those areas should be sealed from the plating solution. Getting the wood grain pattern of some woods has been difficult until recently because the plating solu-

tions tended to penetrate too far into wood. However, treating the wood mandrel with lacquer-like materials can control the penetration so that excellent wood grain reproduction may be obtained. Mandrels with a nonconductive surface must be sprayed with reduced silver which is a liquid silver reduced to a metallic film by the addition of formaldehyde or with a highly conductive silver paint. The first method results only in a 3×10^{-6} in. thickness and, therefore, reproduces far more detail than the paint spray method.

If multiple cavities are required from the same mandrel, the best materials for the mandrels are stainless steel or electroformed nickel. Nickel can be electroformed easily over nickel without sticking to the mandrel. This is because nickel "passivates" readily; it will not accept the plating and leaves a clean parting line. Epoxy mandrels are risky to try to reuse because surface defects can be imparted in removing the electroform from the mandrel. It is often feasible to make any number of cavities from a single mandrel, depending upon part shape and mandrel material. The plating rate is normally 0.012-0.015 in. per 24-hr day. This rate may be increased when plating copper, but stress and brittleness also increase. Plating does go on 24 hr per day, 7 days a week, requiring 9 to 10 days to produce a mold 0.125 in. thick.

Molds are separated from mandrels in three ways. One-piece molds with undercuts require a disposable mandrel which is melted or etched out of the mold. A mold with sufficient draft is pried loose from the mandrel mechanically at one or two points, then, by the use of air pressure, removed completely. An electroformed mold with little or no draft normally can be released by cooling the pattern while heating the electroform. The expansion of the electroform usually will be sufficient to remove it from the mandrel.

Electroformed molds produce extremely accurate reproduction of detail in each cavity when compared with steel for a given price. They have zero porosity compared with alu-

minum castings, and zero shrink when compared with Be/Cu castings. Usually, the electroformed mold is far less costly than steel, comparable in price to Be/Cu, and more costly than aluminum. In some cases electroforming is the only way some molds can be made. However, electroformed molds are relatively soft except in certain cases compared to steel. A practical maximum hardness is about 48 Rockwell C scale. Plating time of two to three weeks also requires a substantial lead time. Delivery of multiple cavities is slow without multiple mandrels or when design changes are to be made compared to aluminum or beryllium castings.

Configuration plays a very important part in electroformed molds because of the difficulty in electroforming to a uniform thickness over the complete surface of the mold. Principles of electromagnetic force dictate that recesses deeper than they are wide, sharp corners, and most internal bosses or projections should be avoided. Some bosses may be inserted into the mandrel as "grow-ins" and the plating will securely attach itself to the bottom of the boss and the "grow-in" becomes an integral part of the mold. Suggestions for matrix design are shown in Fig. 2-12.

There is a version of the electroforming process which largely eliminates the problems of the recesses and cleavage planes. The process was developed in England and is patented there and in this country. It can do jobs that cannot be done any other way and, therefore, has an irreplaceable use in the mold making industry.

The patented English baths deposit a unique quality of metal. The nickel has a hardness of about 45 Rockwell C scale but the elongation at this hardness is 15 percent, which makes the metal very resistant to permanent deformation. The deposit is very even over uneven surfaces. It will deposit metal, for instance, at the bottom of a slot 1/8-in. wide and nearly 1/2-in. deep. Copper has even greater throwing power and sometimes plates faster in the low areas than on the peaks[10].

Nickel electroformed molds have been backed up with a wire arc flame spraying technique in Europe for over 20 yr. It is now used in this country since the development of a light-weight, hand-held unit. It involves the use of an electric arc to fuse or melt the tips of two wires that are fed into the applicator and then sprayed onto a surface. One company involved in this particular application is TAFA Div., Humphreys Corp., Bow, New Hampshire. In this technique, the electroformed mold is reinforced with an integrally bonded outer layer of arc-deposited low carbon steel or aluminum bronze. The coating fills in sharp angles and builds the mold wall to specified thickness to provide both strength and uniform heat conductivity. It also allows very thin-walled electroforms to be used[8].

There are many factors to be considered before a decision can be made as to which route the mold maker will take to construct a mold. All aspects of every job must be considered to determine whether it should be made by hobbing, machining, casting, or electroforming. There is no simple formula to indicate the best method. A minute detail may be the determining factor. As for cavity life, the electroforms will give the same or better life as a hobbed cavity. The surface of the electroform is softer than the hobbing, but the hardness runs deeper. Electroforms also don't stain or rust.

2-5 MOLD REPAIR

It is a simple matter to repair Be/Cu molds by brazing, welding, pinning, or soldering with alloys made specifically for this work. In addition, when a Be/Cu mold is no longer needed, the metal brings a high scrap price.

The repairability of electroformed molds compares favorably with that of other types. They can be repaired by silver soldering, brazing, and welding. Arc welding is not recommended for nickel electroforms because sulfur and other material co-deposited with the nickel lead to fissurelike cracks. The problem can be overcome in wrought nickel
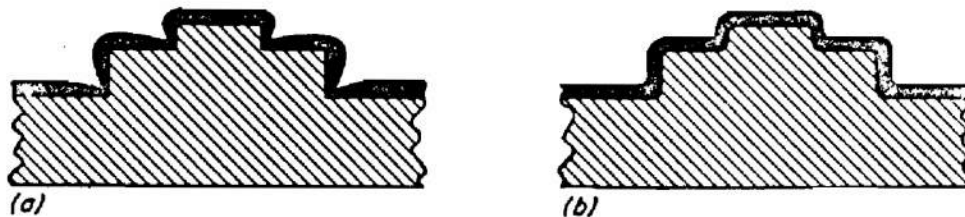
Electrodeposited metal builds up on outside corners and thins
out on inside corners, a. Breaking sharp corners and providing
fillets, b, minimizes variations in metal deposit thickness.

Recesses should be wider than
deep. It is difficult and
sometimes impossible to elec-
trodeposit into deep, narrow
recesses.

Use fillets at least equal to
metal deposit thickness for
strong inside corners.

Holes can be "spotted" for
subsequent drilling by provid-
ing depressions in pattern.

When feasible provide slight
taper (0.001 in. per ft) to aid
mandrel removal.
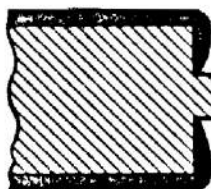
Nonconductive
coating

Eliminate drilling and ream-
ing operations by providing
masked or nonconductive
studs on pattern. Hole diam-
eters can be held to ±0.0002
in. and have excellent sur-
face finish.
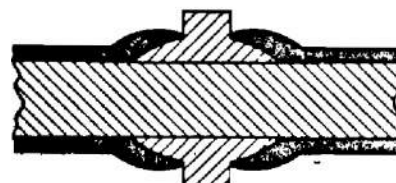
Flanges and bosses should fit
tightly and be flared or ta-
pered to mandrel diameter.

Mondrel

Grown-in
shaft
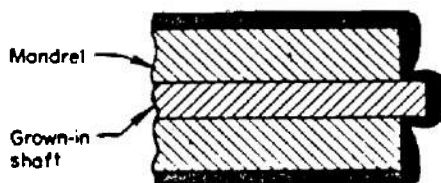
Extend internal piece beyond end
of surrounding part to assure
deposition on sides as well as
end of internal "grow-in" piece.
This provision assures bonding
of internal shaft to outside
cylinder.

ELECTRO MOLD CORPORATION   Minneapolis, Minn.

Reprinted by permission of SPE.

Figure 2-12. Suggestions for Matrix Manufacture

by the addition of manganese, magnesium, or some other additive. Experiments to eliminate it in electroformed nickel by use of additives in the plating bath offer some prospect of success. In repairing a nickel-copper mold, care must be taken because of the heat sink effect of the copper.

Tool steel molds can be repaired or reworked by the use of the electroforming process. Nickel with 45-50 Rockwell C can be added to the spot to be repaired, then machined to a finished size, thus saving a possibly very expensive tool steel mold.

2-6 MOLD RELEASE

To obtain satisfactory mold release, it is recommended that the mold cavities be kept clean and that a proper mold-release agent be used. Molds which have been used previously with vinyl resin or other plastic material may require special cleaning. Sometimes a caustic bath is used. Once the cavities are clean, one of the semipermanent fluid mold-release agents can be applied and heat cured to aid in part removal.

Specific recommendations for mold releases are given in Chapter 7.

Molds also are permanently coated with such materials as polytetrafluorethylene and silicones to facilitate mold release.

2-7 ROTATIONAL MOLD MANUFACTURERS

The following is a list of some of the rotational mold manufacturers in the U.S.:

1. ALLIED PATTERN, INC., Hopkins, Minn.

2. ARROWHEAD PLASTIC ENGINEERING, INC., Muncie, Ind.

3. AUTOMATIC PRODUCTS CORP., Ashland, Ohio

4. BORSE PLASTIC PRODUCTS, INC., Hinsdale, Ill.

5. CONFORMING MATRIX CORP., Toledo, Ohio

6. CONSOLIDATED PATTERN & MFG. CO., St. Louis, Mo.

7. DURO-BRONZE CO., Brooklyn, N.Y.

8. ELECTRO MATRIX CORP., Downers Grove, Ill.

9. ELECTROFORMS, INC., Gardena, Calif.

10. ELECTROMOLD CORP., Trenton, N.J.

11. FILLOUS & RUPPEL CO., Cleveland, Ohio

12. FLAMBEAU PLASTICS CORP., Baraboo, Wis.

13. GERBER, R., ENTERPRISES, INC., Akron, Ohio

14. GERBER, R., ENTERPRISES, INC., Munroe Falls, Ohio

15. HANSON PATTERN & MOLD CORP., Ludlow, Mass.

16. KELCH CORP., Mequon, Wis.

17. KERRCO, INC., Hastings, Neb.

18. KOEHRING CO., SPRINGFIELD CAST PRODUCTS DIV., Springfield, Mass.

19. KOHLER-GENERAL, INC., PLASTICS DIV., Sheboygan Falls, Wis.

20. LOWRY MFG., INC., Holland, Ohio

21. MODERN TOOLS, DIV. OF LOF ENGINEERING PRODUCTS, Toledo, Ohio

22. PAHCO MACHINE, INC., Trenton, N.J.

23. PENTCO, INC., Trenton, N.J.

24. PERFECT DOLL MOLDS CORP., New York, N.Y.

25. PLASTI-CAST MOLD & PRODUCTS CO., Akron, Ohio

26. PLATING ENGINEERING CO., Milwaukee, Wis.

27. PYROLYTIC CO., Barberton, Ohio

28. REUTER, INC., Hopkins, Minn.

29. RINGLER-DORIN, INC., New York, N.Y.

30. ROTO MOLD & DIE CO., Cuyahoga Falls, Ohio

31. ROYALTY INDUSTRIES, INC., Hialeah, Fla.

32. SCIENTIFIC CAST PRODUCTS CORP., Cleveland, Ohio

33. SEGEN, EDWARD D., & CO., Devon, Conn.

34. TECHNI-MOLD & ENGINEERING, INC., Gardena, Calif.

35. THANCO, INC., Grafton, Wis.

36. TOLEDO MOLDING & DIE CORP., Toledo, Ohio

37. TRUEBLOOD, INC., Tipp City, Ohio

38. USM CORP., STANDARD TOOL DIV., Leominster, Mass.

39. UNICAST DEVELOPMENT CORP., Pleasantville, N.Y.

40. VEGAS MOLD CO., INC., Wood Dale, Ill.

41. VERSATILE PLASTICS, INC., Akron, Ohio

42. WESTERN SPECIALTY MFG. CORP., Cheyenne, Wy.

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3. R. E. Duncan, D. R. Ellis, and R. A. McCord, "Rotational Molding", *Encyclopedia of Polymer Science and Technology*, Vol. 9, pp. 118-137, Wiley-Interscience, N.Y., N.Y.

4. G. E. Carrow, "Crosslinkable Rotational Molding High Density Polyethylene", *Society of Plastics Engineers 30th Annual Technical Conference*, Chicago, Ill., May 1972.

5. "Rilsan GSMR Special Grade for Rotational Molding", *Aquitaine-Organico*, No. 168, 1969.

6. "Technical Information on Marlex® Polyolefin Plastics: 17 Rotational Molding", Phillips Petroleum Co.

7. "Rotational Molding of Microthene®

Polyethylene Powder", U. S. Industrial Chemicals Co.

8. J. Frados, *Plastics Focus*, Vol. 5, No. 28, Sept. 10, 1973.

9. J. L. Jansen, "Applications for Electroformed Molds", SPE Regional Technical Conference, *Advanced Methods in Tooling for Molding*, February 23, 1972.

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CHAPTER 3

EQUIPMENT

3-1 MOLD-HANDLING SYSTEMS

The mold-handling system includes all the equipment required to transport the mold (or molds) through the loading, heating, cooling, and unloading steps and to bring about the biaxial rotation typical of rotational molding. The main parts of the system are the spindle, the mold mount (spider), and the drive. These are shown in Fig. 3-1.

There are basically five types of rotomolding systems in use today: fixed-spindle, single-spindle, multiple-spindle, shuttle, and jacketed or ovenless.

3-1.1 FIXED-SPINDLE

This system consists of an oven with a fixed arm rotating about two axes, a cooling chamber with a fixed arm rotating about one or two axes, and a conveyor rack connecting the oven in some manner with the cooling chamber. The basic feature of this machine is that the mold spiders have a quick connecting feature that allows them to be disassembled quickly from the spindles in the oven or cooling chamber. Since the molds are transferred over the conveyor rack from the oven to the cooling chamber and back manually, the conveyor rack can be arranged in a number of configurations.

Two typical arrangements are shown in Figs. 3-2 and 3-3. The fixed-spindle system is used with either hot air or molten heat transfer systems. They involve considerable labor and are essentially noncompetitive in operating costs compared to other systems.

A new concept using only one station per mold has been reported[5]. Unlike the usual systems employing forced hot air convection ovens, this "thermodynamic indexing
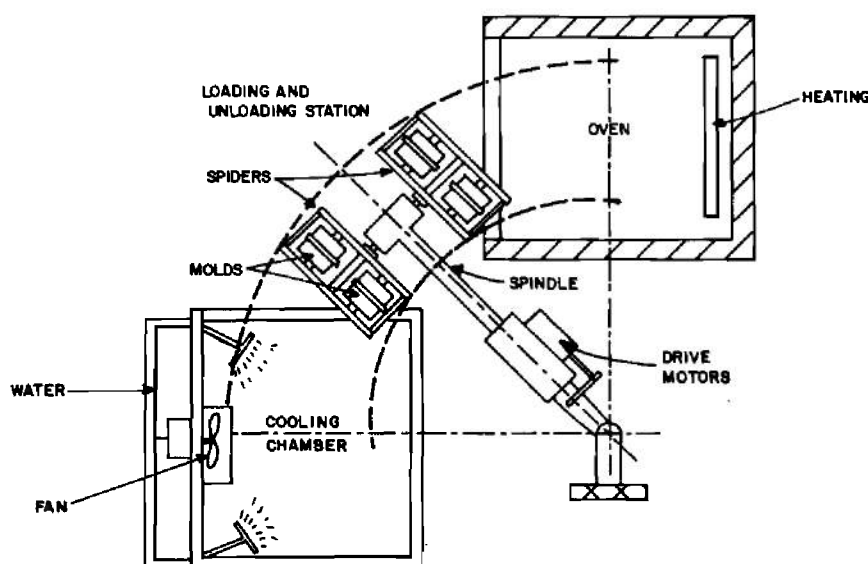
Figure 3-1. Diagram of a Pivoting-arm Rotomolding System
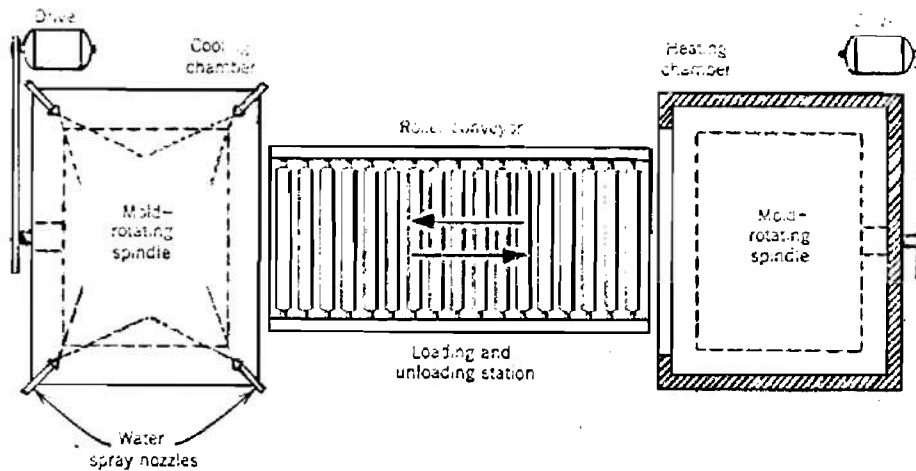
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Figure 3-2. Diagram of a Fixed-spindle Machine [1]

machine" heats the molds in a combustion chamber that operates similar to a jet engine. High-intensity afterburners bring molds up to the desired maximum temperature in a few seconds, then automatically shut off, and the main burners control the uniform temperature until all resin fuses. The molds then remain in the same chamber for water spray and/or air cooling through low- and high-intensity cycles.

An automatic indexing system stops the
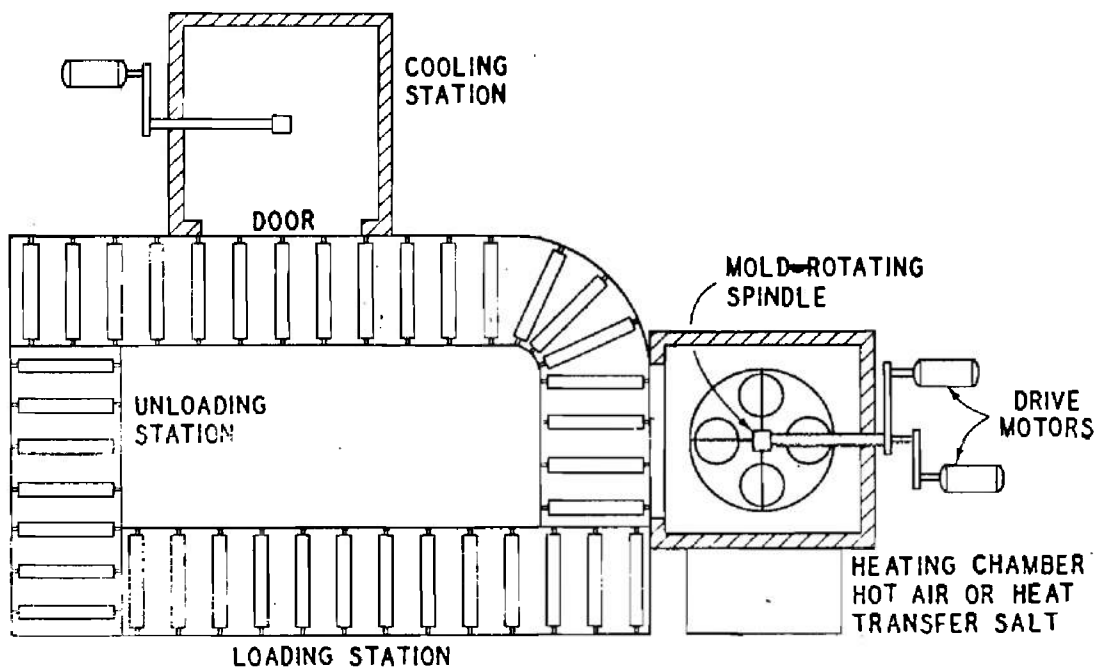
Figure 3-3. Typical Layout of Fixed-spindle Machine [2]

mold at a preset position and reverses the rotation to insure even wall thickness, even in complicated parts. A solid-state control console provides push-button control of up to four or more molds independently by a single timer.

Besides high rate production (about five times greater than standard equipment) the one station has considerably lower space requirements and costs approximately one-third of other units with comparable output[5].

3-1.2 SINGLE-SPINDLE

The single-spindle system is the most basic of the continuous rotation machines. These are used for developmental purposes or, in the case of some large machines, production. In addition, the molding problems associated with new molds can be solved on a single-spindle unit without taking valuable time on a production machine. After the problems are solved, the molds can be transferred to a multiple-spindle production machine.

Two basic configurations of the single-spindle machine are straight line shuttle

and pivot type. The straight line shuttle machine (shown in Fig. 3-4) has the drive motors, spindle, and spindle support all mounted on a carriage that moves on a track. The spindle can then be moved in and out of the oven to the cooling and loading-unloading stations. The oven and cooling chamber doors should have a full opening to allow rotation of the mold to continue as the spindle is moved from the oven to the cooling chamber.

A pivot type single-spindle machine is shown in Fig. 3-1. With this machine the loading-unloading station is located between the oven and the cooling station. With the addition of another spindle and cooling chamber this unit can be made into a two-spindle machine. The two-spindle machine can be used for development work and limited production work at the same time.

3-1.3 MULTIPLE-SPINDLES

The continuous machine remains by far the most popular in the small-to-large size range. A continuous machine includes 3, 4, or 5 spindles located in a circular pattern and equidistant from each other. Each arm or spindle functions with complete
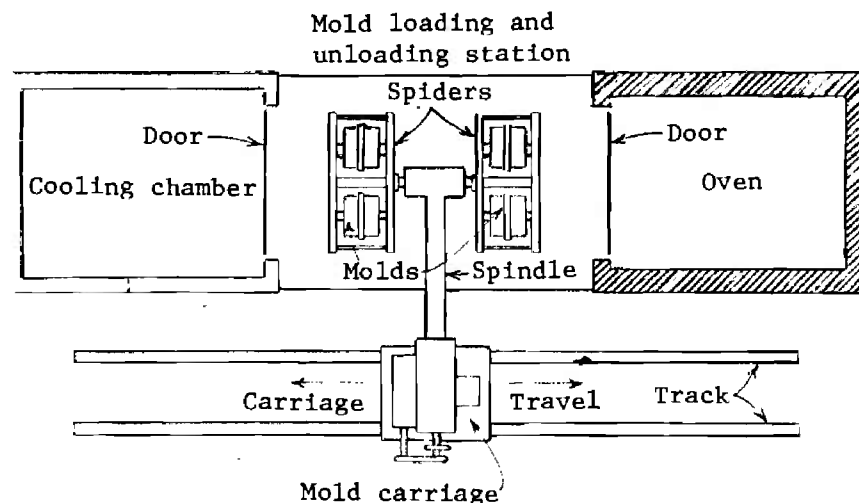
Reprinted by permission of John Wiley & Sons, Inc.
Figure 3-4. Diagram of a Single-spindle Rotational-molding Machine[1]

3-3

independence as to speeds and ratios of rotation, and extends from a common hub that indexes intermittently, permitting movement of arms from station to station.

Machine configuration may be vertical, similar to a ferris wheel or horizontal, similar to a carrousel.

Each spindle contains its own set of molds; each set may be totally different from those carried by the other spindles. There are three stations—the loading and unloading area, the heating chamber, and the cooling chamber. All portions of the cycle are fully automatic with the exception of loading the materials and unloading finished parts.

Illustrations of a three- and four-spindle machine are given in Figs. 3-5 and 3-6, respectively.

Extra stations sometimes are added in multiple-spindle systems to increase productivity. For example, an extra oven can be used in a three-spindle machine when the heating cycle is twice as long as the other cycles. The spindle is merely moved from the first oven to the second to complete the heating cycle.

The extra station position on a four-spindle machine is used in some cases to separate the mold unloading and mold loading stations into two stations. This can help overcome problems where insufficient time exists in a given cycle for mold rework. This configuration is particularly helpful where numerous molds are used on each arm.

3-1.4 SHUTTLES

The multiple-spindle units have been
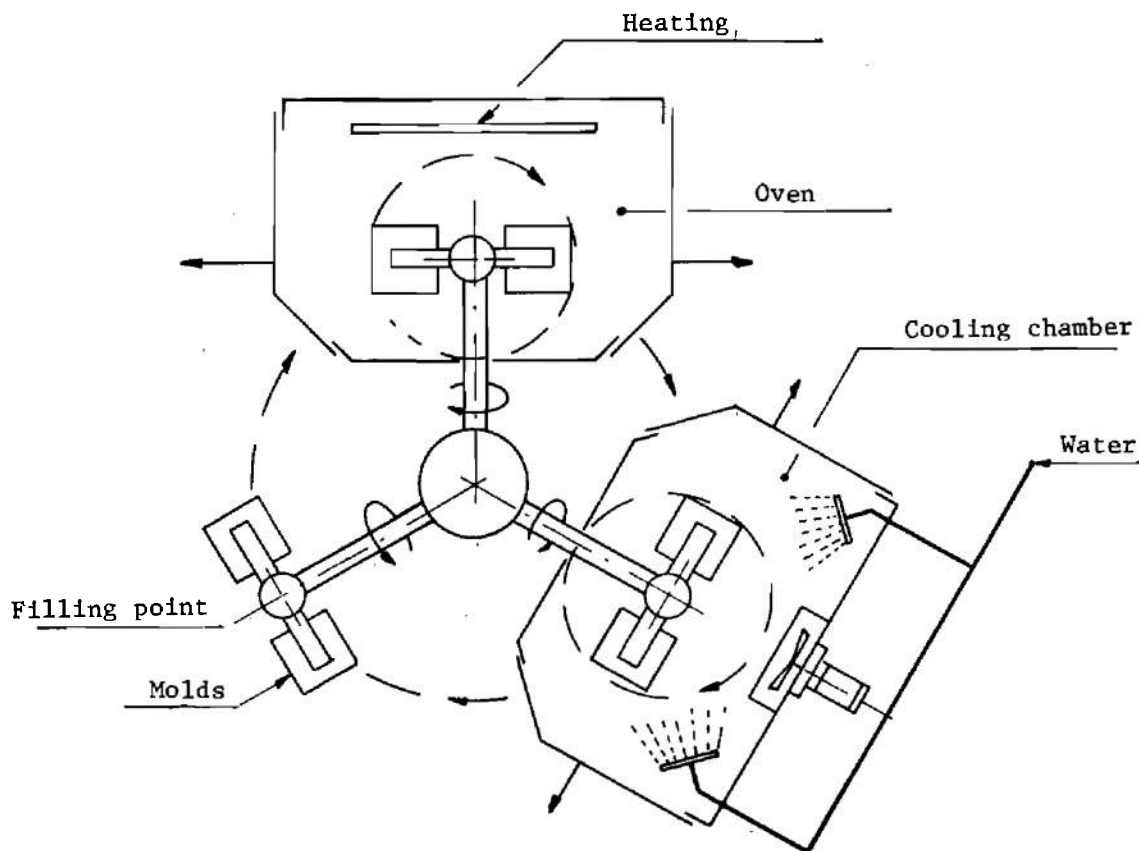
Figure 3-5. Three-spindle Unit[3]

modified to accommodate extremely large molds (approximately 204 in. diameter and 5000 lb) on each arm similar to a locomotive turntable.

The mold is shuttled from station to station by a rotating center hub, which receives each arm as it returns from a phase of the cycle, then indexes it to the next station. A mold is filled with material in one station, then shuttled from the loading station onto the turntable where it is indexed and pointed in the direction of the oven. The mold then continues along into the oven station, where it is rotated and heated simultaneously.

Molds are supported on both sides and are contained on a carrier similar to a locomotive flat car. One, two, three, four, or more shuttle cars may be employed because the machine is of modular design. One mold-carrying car and three basic stations may be installed initially with additional cars and stations being added as production increases warrant. Due to the size of the machine, it is necessary to erect it on-site.

Operation is semiautomatic with an operator controlling the position of each arm and function of each station from a central control area. Oven times, heats, cooling times, etc., are all automatically controlled; and heating is accomplished by hot air from either gas-fired (natural or propane) or oil-fired ovens. A diagram of a six-station system is shown in Fig. 3-7.

3-1.5 JACKETED AND OVENLESS UNITS

Fig. 3-8 depicts a jacketed mold system. This system consists of a single station wherein cavities are encased by a second layer of metal with spacing between the outer shell and inner cavity. First hot, then cold liquid are circulated throughout this area while the mold rotates. No heating ovens or cooling chambers are required, and the mold is not transferred between stations.

Its advantages include high production runs of symmetrical configurations and lower cycle times. Possible seepage of heat transfer liquid into the mold cavity and limited part design are some of the limitations of this system.

This unit represents the most sophisticated molds and tooling of all handling systems. Molds can cost five times as much as those for other rotomolding machines.
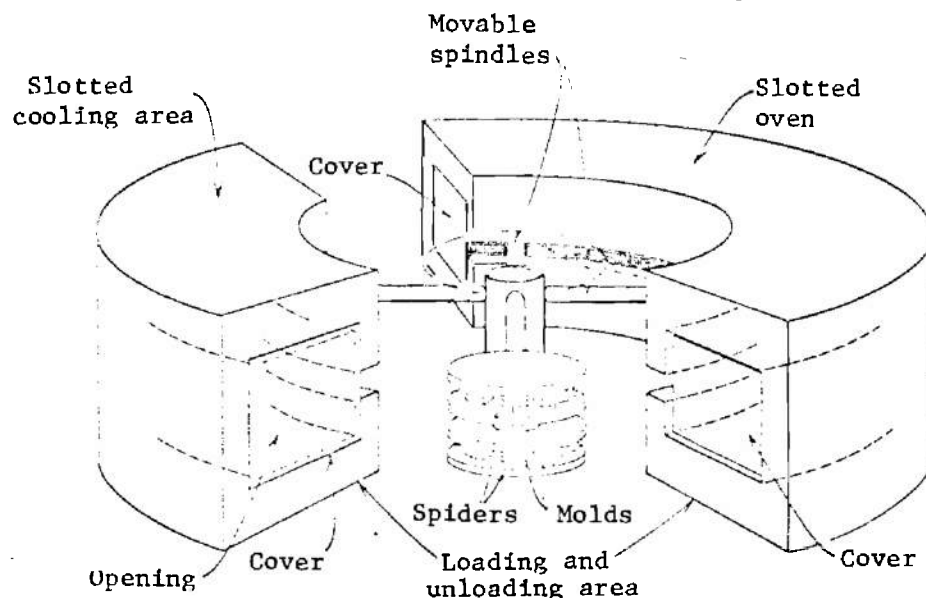
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Figure 3-6. Four-spindle Unit[1]
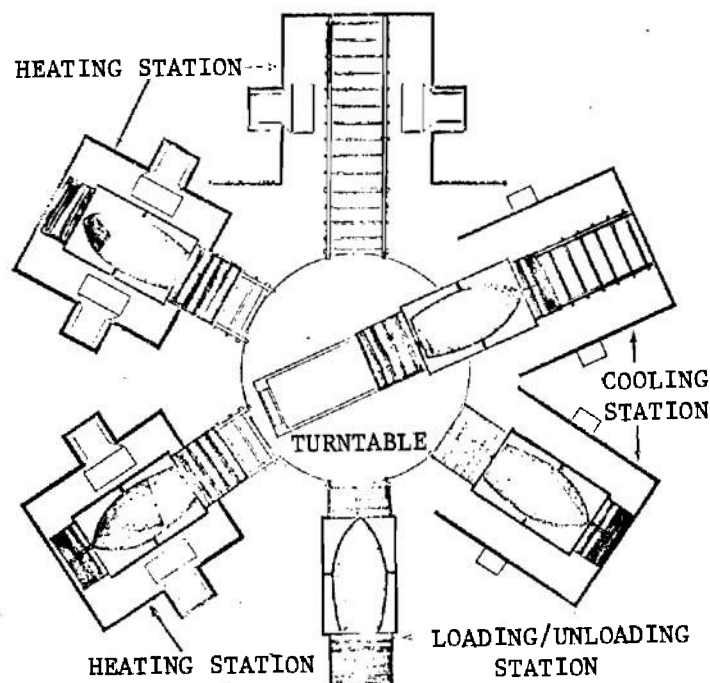
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Figure 3-7. Diagram of the Layout of a Six-station McNeil Rotational Molding Machine (Requires floor space 75 by 75 ft, with 20-ft height[a])

In a somewhat similar application, one particular machine directs an open gas flame against the mold surface while the mold is spinning around one axis and rocking about another axis. These are custom units for specialized use. The danger of uneven heating with "hot spots" would be one major limitation.

3-2 BIAXIAL DRIVE SYSTEMS

A variety of drive systems is available to provide biaxial rotation of the molds. They include either a variable-speed drive or constant-speed drive with interchangeable gears or chain sprockets.

Most rotational molding is carried out with a 10- to 15-rpm rotation of the major axis and a 2- to 3-rpm rotation of the minor axis, i.e., an average ratio of 4 or 5 to 1. However, provisions should be made for changing the ratio to correct nonuniform powder distribution and wall thickness which can occur at the average rotation ratio. If many different parts are to be produced on one machine, variable-speed drives are recommended to eliminate the need to change gears or sprockets when changing speed or ratio of rotation. If the drive allows for variable-speed rotation of each axis independently over a range of 1 to 35 rpm, any practical rotational ratio can be obtained.

Fig. 3-9 shows the drive system for a double centerline mounted biaxial rotation system.

3-3 SPIDERS

See par. 2-3.5.
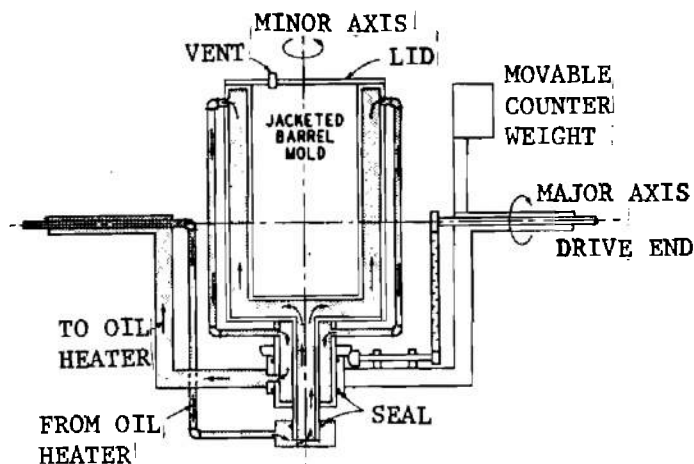
Figure 3-8. Typical Arm Layout of Open-end Mold on Jacketed Mold Machine[2]

3-4 MOLD FILLING

Many attempts at automating the mold opening and loading sequence have been tried in past years. However, due to the diversity of parts that can be molded simultaneously on the equipment, it has proved rather unsuccessful. Complete automation of mold unloading and polymer filling are feasible only on very high production runs of the same part. The technology is available for complete automation, but it seems that automatic resin weighing systems are the extent of automation feasible at this time. As the use of hygroscopic materials increases, it is probable that a system incorporating resin drying, weighing, and conveying the powder into the mold will become common ancillary equipment for the rotational molder.

3-5 MOLD HEATING SYSTEMS

Present mold heating methods are hot-air convection, hot-liquid conduction, infrared radiation, and direct gas-jet flames.

3-5.1 HOT-AIR CONVECTION HEATING

Hot air is the most commonly used heat source for rotational molding. Either gas-fired, oil-fired, or electrical heaters can be

used to heat the air. This heat source is particularly suitable for thin-walled molds. Oven temperatures may vary from 400° to 900°F (205°–490°C). The higher the oven temperature, in this range, the shorter the heating cycle.

Accurately directed air flow is important. This can be obtained by baffling the air blower. Equally important are the velocity of the air and uniformity of the temperature throughout the oven. A high-velocity scrubbing action is needed for maximum heat transfer. Usually, a minimum velocity of about 2,500 ft³/min per 100 ft³ of oven volume is desirable.

Hot spots in the oven must be avoided when items of uniform wall thickness are to be molded. Excess heat capacity of the oven is desirable so that the required operating temperature can be attained rapidly after insertion of the cool, charged mold. If temperatures are changed frequently, a recording temperature controller is recommended.

3-5.2 HOT-LIQUID CONDUCTION HEATING

Heating by means of hot-fluid sprays in ovens also is used. A noncorrosive, eutectic

mixture of inorganic salts commonly used for heat treating of metals is the heat transfer medium. Solvents are not used in these sprays. Operating temperatures normally are in the range of 450°–550°F (230°–290°C). The heat-transfer liquid is brought up to operating temperature in a melting tank, or reservoir, containing gas fire tubes or electrical immersion heaters. A heating period of up to 2.5/hr, depending upon the volume of heating medium used, is required to reach operating temperature. The fluid is pumped through a network of spray nozzles onto the rotating mold assembly. It is important that the melting tanks have enough capacity to maintain the operating temperature throughout the heating cycle. The temperature drop in the melting tank should not exceed 10–15 deg F (5.5–8.5 deg C) during the mold-heating cycle.

In this heating system, heat is transferred by conduction rather than convection. Hot-liquid spraying, therefore, normally heats the molds faster than hot air. It is generally better suited for molding pieces with heavy walls and for the production of more complex shapes. However, precautions are needed to avoid part contamination and to insure uniform distribution of the liquid over the mold.

The molds usually are rinsed with water to remove the heating fluid before leaving the oven. Since unrecoverable heating fluid can mean the difference between profit and loss in hot-liquid spray heating, it is essential that such equipment have a good system to recover and reuse the heating medium. Several patents have been issued recently for improved salts recovery.

Hot-liquid conduction heating also is used in jacketed molding. In this instance hot oil is pumped through the hollow double-walled mold. This system permits fast heating cycles,
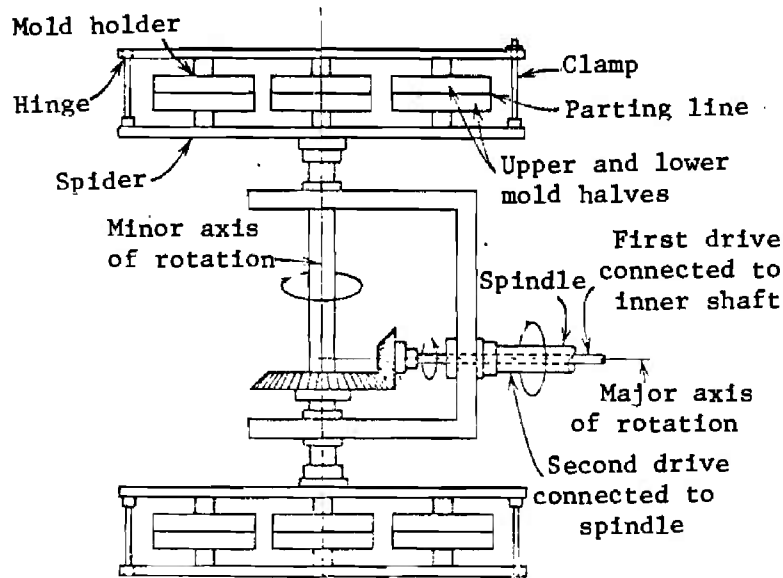
Figure 3-9. Mechanism of Biaxial Rotation.[1] (The spindle is turned on the major axis while the molds are rotated on the minor axis. The ratio of the two simultaneous rotations is determined by the gear, which may be exchangeable, or by two motor drives.)

economical use of heat since only the molds are heated, and very accurate temperature control.

3-5.3 INFRARED HEATING

Infrared heating with either gas-fired or electrical radiation heaters is used on special-purpose and prototype rotational-molding equipment primarily.

Heating with infrared is very fast and efficient, but the heat source is limited to molding simple shapes and single molds. Multiple or complex-shaped molds cannot be heated by infrared because the radiant heat cannot strike all parts of the mold uniformly. Shielded areas of the mold will not attain as high a temperature as exposed parts of the mold surface. Consequently, thin spots will occur in the wall of the molded item.

3-5.4 DIRECT GAS FLAME

In addition to the heating methods named previously, direct gas flame can be used. However, it is usually troublesome, especially when a variety of products must be made,

because heaters must be designed to the shape of each mold to insure uniform temperatures around the mold. The same disadvantage applies to electrical resistance heating and induction heating.

3-6 MOLD COOLING

Molds are cooled by air, water, and oil. Spraying with water is the most common method of cooling the mold. This is done while the mold is biaxial rotating. Failure to rotate the mold during cooling will result in the soft molten polymer sagging to the bottom of the mold. Well placed, highly atomized water sprays produce uniform and rapid cooling. Blowers or compressed-air nozzles in the cooling chamber also are used. For critical cooling applications, air and water can be used intermittently externally on the mold surface or internally via mold blanketing (see par. 3-7).

Quick cooling is economically desirable. However, too rapid cooling can cause part warpage. Therefore, a combination of air and water spray for an appropriate cooling cycle is common.
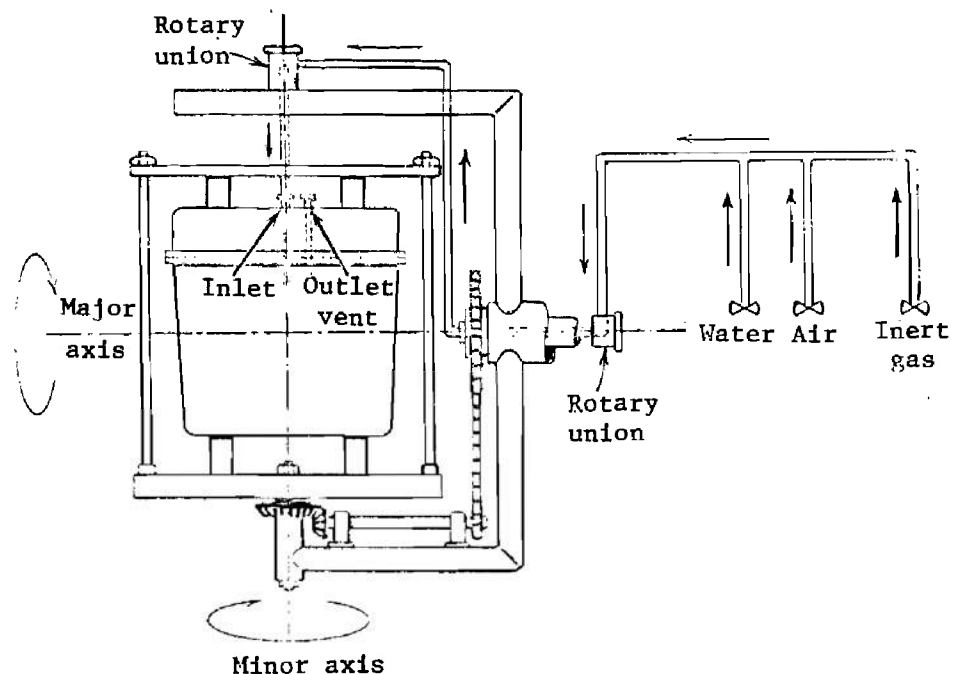
Figure 3-10. Diagram of Typical Auxiliary Equipment for Introducing Gas,
Cool Moist Air, or Water into a Rotational Mold[1]

In jacketed molds, cooling is accomplished by replacing hot oil with cool oil in the hollow mold walls surrounding the cavities. By proper pumping techniques, instrumentation valving, and controlled oil temperatures, accurate cooling cycles can be achieved.

3-7 INTERNAL MOLD BLANKETING

Equipment through which inert gas and cooling media can be introduced into and vented from the mold during the heating and cooling cycles is recommended for rotational molding. The inert gas and cooling media are introduced into the mold through hollow rotating drive shafts, mechanical seals, and a flexible high-temperature hose inserted in the mold as shown in Fig. 3-10.

3-8 ROTATIONAL MOLDING EQUIPMENT SUPPLIERS

The following are prominent equipment suppliers:

1. Automated Manufacturing Systems, Inc., Hickory, N.C. (2)

2. E.B. Blue, Co., S. Norwalk, Conn. (1, 3)

3. Infra-Ray Div., Solaronics, Inc., Cleveland, Ohio (1)

4. McNeil-FEMCO-McNeil Corp., Cuyahoga Falls, Ohio (1, 2)

5. Officine Meccaniche Caccia, San Macario, Italy (1)

6. Roto Mold & Die Co., Cuyahoga Falls, Ohio (2)

7. Rototron Corp., Farmingdale, N.Y. (4)

8. Turner Machinery Ltd., Bramley, Leeds, England (1)

9. Versatile Plastics, Inc., Akron, Ohio (5)

The following numbers—inclosed in parentheses after the supplier's name and address—indicate the type of equipment supplied:

(1) Hot-Air Ovens

(2) Jacketed Mold

(3) Molten Salts

(4) Direct Flame

(5) Combustion Chamber

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2. "Technical Information on Marlex® Polyolefin Plastics: 17 Rotational Molding", Phillips Petroleum Co.

3. "Rilsan GSMR Special Grade for Rotational Molding", *Aquitane-Organico*, No. 168, 1969.

4. Anon, "Rotational Molding Reaches New Dimensions", *Plastics World*, Vol. 28, No. 2, Feb. '70, p. 60.

5. Versatile Plastics, Inc. *Thermodynamic Indexing Machine*, unnumbered, 1973.

CHAPTER 4

PROCESSING PARAMETERS

4-1 GENERAL

There are six basic steps associated with the powder molding of a finished product:

1. The bottom cavities of the unheated molds are charged with a predetermined weight of powder desired in the end product.

2. The mold parts are clamped in place on a spider. When one or both ends of the pieces are open, heat-insulating covers are used to close the mold.

3. The charged molds are placed in an oven, where they are heated while simultaneously rotating around two axes in planes at right angles to each other.

4. The double revolving motion results in formation of hollow objects in every mold cavity, the powder being evenly distributed to form walls of uniform thickness when the resin fuses, except where heat-insulating covers are used. Weight and wall thickness of the molded items can be modified by increasing the amount of powder initially put into each lower mold cavity.

5. When all the powder has fused into a homogeneous layer on the walls of the cavities, the mold is cooled while still being rotated.

6. The mold is opened and the molding is removed. Then the mold is readied for the next cycle.

These steps are required whether the machine is an automatic three- or four-spindle unit or if the machine is a manual single-spindle unit. Today's machines have automated this process to the point where the operator simply must load the powder material into the mold, press the cycle button, and remove the finished product from the mold cavity. Tomorrow's machine will probably automatically load and unload the mold, eliminating the operator.

The paragraphs that follow describe the phenomena which must be considered in determining the parameters for each of the processing steps listed.

4-2 RESIN POWDER CHARACTERISTICS

The part quality greatly depends upon the resin being used. The selection of a resin for rotational molding involves the consideration of physical and chemical properties of the powder resin, and particularly the powder properties; i.e., size, shape, and uniformity.

4-2.1 POWDER PARTICLE SIZE, SHAPE, AND DISTRIBUTION

The powder properties of ground resin are determined by measuring the pourability, mesh size, particle distribution, and bulk density. The pourability is an indication of the fluid-like flowing properties of the powdered resin within the mold. ASTM Procedure D1895-69 is used to measure this property. For example, a value of 185 g/min or greater generally is considered adequate for most high-density polyethylene applications[1].

Mesh size and particle distribution normally are determined by screening the powder through U.S. Standard Sieves. Mesh size is the minimum U.S. Standard sieve size which will pass 95 percent or more of the powder. ASTM Procedure D1921-63 Method A or B is

used to determine mesh size.

Table 4-1 shows the opening sizes for a number of standard sieve series.

TABLE 4-1

UNITED STATES STANDARD SIEVE SERIES[1]

MESH SIEVE NO.	SIEVE OPENING SIZE		
	MICRONS	INCHES	MILLIMETERS
10	2,000	0.0787	2.00
16	1,190	0.0469	1.19
20	840	0.0331	0.84
35	500	0.0179	0.50
50	297	0.0117	0.297
60	250	0.0098	0.250
80	177	0.0070	0.177
100	149	0.0059	0.149
200	74	0.0029	0.074

Heat is transferred to a particle through contact with other particles, the mold surface, and contact with the surrounding air. Heat transfer from air convection is poor compared with contact conduction heat transfer. For a flat sheet of thickness R, the surface to volume ratio (a measure of the efficiency by which heat is transferred through the particle surface and into the particle interior) is $1/R$ for air convection. For a cube of side R, it is $6/R$ and for a sphere of radius R, it is $3/R$. However, for contact conduction, if only one portion of the particle is in contact with a heated surface, the surface to volume ratio becomes $1/(2\,R)$ for a flat sheet, $1/R$ for a cube and zero for a sphere. Thus, the more spherical a particle becomes, the smaller the area for contact heat transfer. Therefore, the rate at which powder melts is a function of the shape of the powder[2].

Heat transfer should improve with decreasing particle size. The smaller the characteristic dimension R, the larger the surface to volume ratio and the more efficient the contact heat transfer becomes. Therefore, powder of 35 mesh generally is used in rotational molding rather than extruder grade pellets or granules.

There are limitations on lower powder particle size. Finer powders present molding problems and increase grinding costs substantially. Grinding of some powders to 100-140 mesh leads to excessive shearing and heating of the polymer. This results in losses in material strength and produces undesirable product characteristics such as discoloration. Also, tumbling of very fine powders within a mold will build up high static charges that aid in agglomerating the powders. This leads to uneven melting and nonuniformity of part wall thickness. Surface adsorption of moisture also is enhanced which can cause powder agglomeration and part defects.

However, some fines should be included in rotocasting powders. Occlusion (or pore) density in part surfaces is strongly affected by fines concentration. Further, fines aid powder flow during mixing and tumbling apparently by lubricating the larger particles and smoothing flow.

The proper proportion of fines to coarse powders has not been established for all plastics. Table 4-2 gives particle size distributions for several commercially available plastics. These were determined by roto-tapping the plastics up to 8 hr on a multiple sieve shaker table and then weighing the amount of powder retained on each sieve. Certainly the most important criterion on particle size distribution is whether a useful article can be made using commercially available particle size distribution. Since this is the case, it must be concluded that the 35 mesh grind presently offered by custom grinders and resin suppliers is satisfactory.

The shape of the particles plays an important role not only in heat transfer but in the flow of the powder during rotation. The flow behavior of very flat particles, such as flake or cubes, is difficult to predict. This is due to the alternate slipping and sticking of the material on the rotating surface. There-

TABLE 4-2

POWDER PARTICLE SIZE DISTRIBUTIONS[2]

MATERIAL	GRINDER	+30 MESH	−30 TO +50 MESH	−50 TO +70 MESH	−70 TO +100 MESH	−100 MESH
Rexene 324C8 polystyrene	Wedco, Inc., nominal −35 mesh	0.0	60.2	22.7	11.0	6.1
Rexene 324C8 polystyrene	Wedco, Inc., nominal −80 mesh	0.0	0.0	0.1	75.3	24.6
Cosden high impact polystyrene	No grind, bead precipitated	0.2	82.2	10.9	5.6	1.1
USI Chemicals Microthene LDPE	none, as received	0.5	42.6	22.4	18.6	15.9

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*A minus sign preceding a mesh size means all powder passes through the screen; a plus sign, all powder retained on the screen.

fore, trial and error experimentation is required to determine flow patterns and cycle times.

Cylindrical particles with large aspect ratios (L/D ratios) pose molding problems of a different type. Powders that have been ground but not polished or tumbled for some time against an abrasive surface usually have tails on the order of 10 μ in diameter and 500 to 1,000 μ long. These tails are attributed to partial melting of the material during grinding and likened to cylinders with large aspect ratios. Parts produced with unpolished powder are usually more difficult to mold and are mechanically inferior to parts made with polished powder. This is attributed to particle entanglements, air entrainment, and occlusion owing to the coiling of these tails. Some shapes of rotational grade materials are shown schematically in Fig. 4-1.

From a heat transfer and fluid flow processing viewpoint, the most desirable particle size is between 35 and 75 mesh and the most desirable particle shape is cubic with very generously rounded corners. Fines should be included to aid both heat transfer and powder flow. Tails should be removed to prevent detrimental part properties.

4-2.2 POWDER THERMAL DIFFUSIVITY

Another powder characteristic is thermal diffusivity, defined as the thermal conductivity divided by the product of the density and the specific heat. This physical property is strongly dependent upon the density of the powder. Unfortunately, it is not normally tabulated in the literature. Since the rate of heat transfer to the powder is directly proportional to the square root of the thermal diffusivity, it is necessary to obtain values that can be used with confidence. Methods for calculating thermal diffusivity derived by Rao and Throne are given in par. 4-6.3.

4-2.3 POWDER VISCOSITY

The predominant force causing polymer melt flow within the mold is gravity. This force leads to very low shear stresses. While some data on flow in the low-shear or near-Newtonian spectrum of shear rates are available in the technical literature, most resin manufacturers do not provide this information.

Since this system is thermally transient, the temperature dependency of the viscosity of the materials is required. Fortunately, these

(A) Spheres

(B) Irregular shapes

(C) Rounded cubes

(D) Smooth cylinders or spheres
with tails

(E) Cubes with large radius
corners
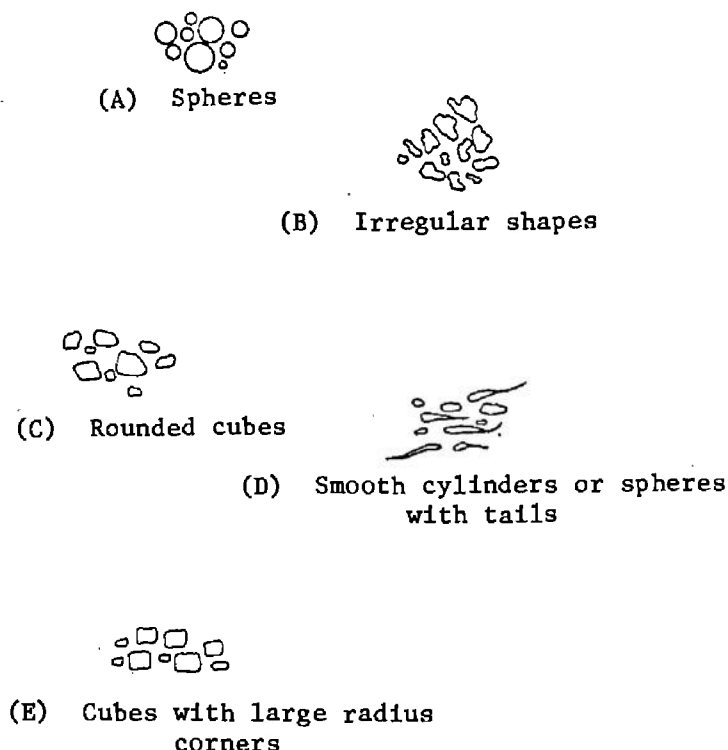
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Figure 4-1. Powder Particle Shapes[2]

data are more readily available than zero shear viscosity data. However, small material changes such as the addition of internal lubricants can drastically affect both values and these effects are rarely reported by the resin manufacturers.

4-2.4 POWDER MELT TEMPERATURE

The melting temperatures of many commercially available polymers are available from the resin suppliers. However, in rotational molding, the melting temperature is not as important as the temperature when the polymer becomes sticky or tacky. This is the temperature where the powder releases from the mold or melt surface, to fall back in the mixing step during rotation. The efficiency and cleanness of release depend upon the tackiness of the melt. If large amounts of powder stick to the melt, the time of final melting and rate of melting would be incorrect unless the temperature at which the material becomes tacky were used. This temperature (designated as T_M) usually is unknown and must be determined by trial-and-error.

The values for the amount of energy required to melt a polymer are from zero for amorphous materials such as polystyrenes to approximately 80 Btu/lb for Hercules Hi-Fax 1400 polyethylene and 120 Btu/lb for du Pont's Zytel 101 NCLO nylon[3]. In general, except for the highly crystalline materials such as high-density polyethylene or Teflon®, the melting temperature range of any plastic is broad; and, hence, the additional energy requirements can be included as an exceptional temperature-dependent specific heat. This assumption clearly simplifies computation and energy balances, since it is not necessary to account for latent heat changes at the interface between liquid and solid. (See Ref. 4

for comments regarding crystalline materials.)[2]

4-2.5 PIGMENTATION

Color compounding and dry blending are the basic coloring techniques used for rotational molding. Since there is no working of the melt during molding, compounded color concentrates are not recommended.

4-2.5.1 Color Compounds

Color compounded powders are prepared by hot compounding the color in the resin and then pelletizing. The colored pellets are then ground to powder. Color compounded powders have the best pigment dispersion and retention of the base resin physical properties. They also allow the use of brighter more opaque colors since greater pigment loading is possible, without loss of physical properties, than with dry blends.

4-2.5.2 Dry Blend Coloring

Dry blend coloring is satisfactory for many applications. Good pigment dispersion in the powder is necessary for good appearance and for the development of the optimum physical properties. Intensive mixers (Henschel or Cowles) are preferred because of their speed, ability to disperse pigments evenly, and elimination of pigment agglomerates. Low intensity mixing techniques such as ribbon blenders, double cone blenders, or drum tumblers may be satisfactory if proper techniques are used.

Dry blending techniques are very important. To retain optimum impact strength, pigment loadings should be kept as low as possible. For example, they should be below 0.5 percent for high-density polyethylene (HDPE), and even at these loadings some pigments drastically affect impact strength[1].

4-3 MOLD CHARGING

Molds may be filled manually or automatically. Manual filling is advantageous when filling different colored items simultaneously in a multiple-cavity mold. For long runs, automatic mold-filling equipment is helpful. Since bulk density, measured in lb/ft^3, of powdered resin can vary permitting differences in wall thickness, the powder charge should be based on a weight measurement.

4-4 CLAMPING

Many types of clamping devices are used. Where individual molds are mounted without a spider, C-clamps or vise grips are sometimes clamped on the parting line flange. Usually molds are mounted on a steel spider and held together with a group of bolts or adjustable overcenter clamps. If motorized impact wrenches are used with the bolt technique, either method could be satisfactory for production. (See par. 2-3.5.)

4-5 MOLD ROTATION

The uniform continuous deposit of powdered resin on the interior surface of the mold is achieved by rotating the mold in two directions (perpendicular axes of rotation) simultaneously while it is being heated. The rotational molding spindle provides this type of movement. This allows various ratios of major to minor axis rotation in addition to speeds of rotation, both of which are important in obtaining uniform deposit of powder.

Most rotational molds are placed on the rotating spider so that no portion of the mold is directly over the centerline of the major axis. This is because, regardless of the minor axis rate of rotation, the minor radial acceleration at the polar center is zero. Thus powder in this region is affected only by

major axis rotation. At the outer edge of the mold fixture, this radial acceleration — determined by the rate of rotation of the minor arm — is at a maximum. Likewise, major speeds at the outer rim are not much greater than those at the polar center in relatively flat configurations. Thus, the local ratio of minor to major radial accelerations may vary from zero at the polar center to values in excess of unity at the outer rim of the molds. Therefore, the shape of the mold, size, number of molds per spindle, and distance from the two axes combine to influence the speed and ratio of rotation needed for each operation. Generally speeds are below 20 rpm.

Regular shaped parts with their longest dimension mounted parallel to the major axis will use a ratio in which the major axis speed is greater than the minor. A common ratio is 3.75 to 1. If the longest dimension of an item such as a wastebasket is mounted perpendicular to the major axis, an inverse ratio generally is needed. A typical example would be 1 to 3.75. The proper rotation for a given mold set-up is found by making a few experimental runs to observe the results of various speeds and ratios.

Table 4-3 gives some suggested rotational ratios and typical axial speeds for various shapes as determined by molding experience.

Fig. 4-3 illustrates the effect of speed on oven cycle time at an oven set temperature of 750° for a polymer melt system of 200°F.

It is observed that the faster the speed, the shorter the contact time and the thinner the penetration layer. However, the faster speed results in more rapid mixing. Therefore, high rpm and high set point temperatures are desirable for short operating cycles.

4-6 HEATING CYCLE (OVEN CYCLE TIMES)

The total heating cycle (OCT) consists of four parts:

TABLE 4-3

ROTATION RATIO FOR TYPICAL SHAPES
(from McNeil Akron Corp.)

RATIO	SHAPES	TYPICAL SPEED, rpm	
		MAJOR AXIS	MINOR AXIS
8 to 1	Oblongs (horiz. mounted) straight tubes	8	9
5 to 1	Some defroster ducts	5	6
4.5 to 1	Balls or globes	8	9.75
3.3 to 1	Any shape showing over-lapping lines of rotation at 4 to 1	10 12	12.25 14.5
4 to 1	Cubes, balls, odd shapes	8	10
	Rectangular boxes, horses with bent legs	10	12.5
2 to 1	Rings, tires, balls	6	9
	Any rectangle which shows two or more thin sides when run at 4 to 1	8	12
	Picture frames, Manikins, Round flat shapes	10	15
	Horses with straight legs Auto crash pads (vert. mounted)	12	18
1 to 2	Parts which should run at 2 to 1 but show thin side walls	5 7	15 21
1 to 3	Flat rectangles (gas tanks, suitcases, tote bin covers)	4 6 9.5	15 22.5 36
1 to 4	Tires, curved air ducts	4	20
	Pipe angles, flat rectangles	5	25
	Balls whose sides are thin at 4 to 1 ratio, vertical mounted cylinders	6	30
1 to 5	Vertical mounted cylinders	4	24
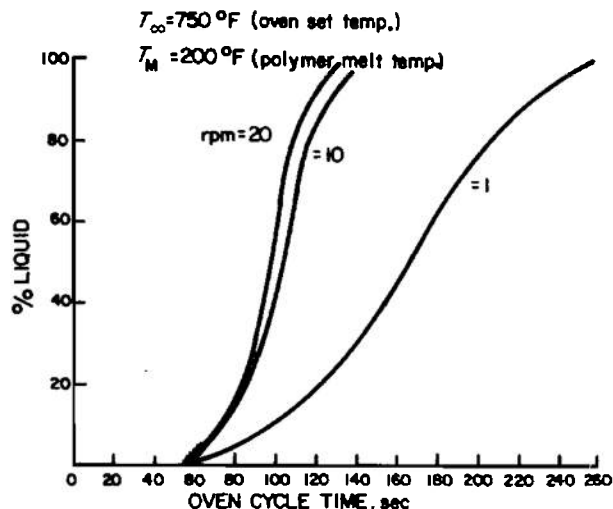
Figure 4-2. Effect of rpm on Melting Rate for $T_\infty = 750°F$, $T_M = 200°F^2$

1. Time required to heat the mold

2. Time required to heat all the powder to the melting temperature

3. Time required to sinter the material into the three-dimensional network

4. Time required to densify the material into a nonporous, bubble-free homogeneous cross section.

These functions are dependent on the variables described in the paragraphs that follow.

4-6.1 HEAT MEDIUM, VELOCITY, AND OVEN SET TEMPERATURE

4-6.1.1 Heat Medium

Classical heat transfer considerations state that heating by liquid to solid convection is a considerably faster technique than gas to solid convection. The heat transfer coefficient for hot oil is about 50 times greater than that for air; condensing steam 1000 times greater than that for air.

If one assumes that all variables are set to the same value on a molten salt heat machine and a forced hot air machine, the OCT ratio (air to salt) would fall in a range from 25:1 (for the best possible salt heat vs the poorest hot air heat) down to 3.3:1 (for the best possible hot air heat vs the poorest salt heat)[5].

4-6.1.2 Heat Medium Velocity

Also there are situations in which two different salt heat machines have OCT ratios as great as 2.5:1 with all controls set to the same value. This is a function of the velocity of the salt over the mold surface. This might also occur within a group of molds on a "spider".

Ratios up to 3:1 have been found among forced hot air machines with all variables set to the same values because air velocity is not controlled in a standard fashion. For example, by doubling the air rate in laboratory machines OCT were decreased by 24 percent at 400°F and by 37 percent at 600°F[5].

4-6.1.3 Oven Set Temperature

If the effect of oven set temperature and air circulation rate are examined, even greater

differences will result. As shown in Fig. 4-3 high velocity air at 600°F yields an OCT which is only 27 percent of the OCT at 400°F with low velocity air. This represents an OCT ratio of 3.6:1.

4-6.2 TRANSIENT HEATING OF MOLD SURFACE

Metal molds used for rotational molding are introduced into a hot isothermal environment from mold room temperature. Owing to the large heat capacity of the materials used (steel, stainless steel, copper, nickel, aluminum), the molds heat slowly to the temperature of the oven. The heating curves for an aluminum mold with 1/8-in. walls at 450° and 750°F are shown in Fig. 4-4.

According to transient heat conduction theory based on Rao and Throne experiments[2], the mold temperature T is

KEY:

x $T_{oo} = 750\,°F$, MOLD TOWARD DOOR

□ $T_{oo} = 450\,°F$, MOLD TOWARD DOOR
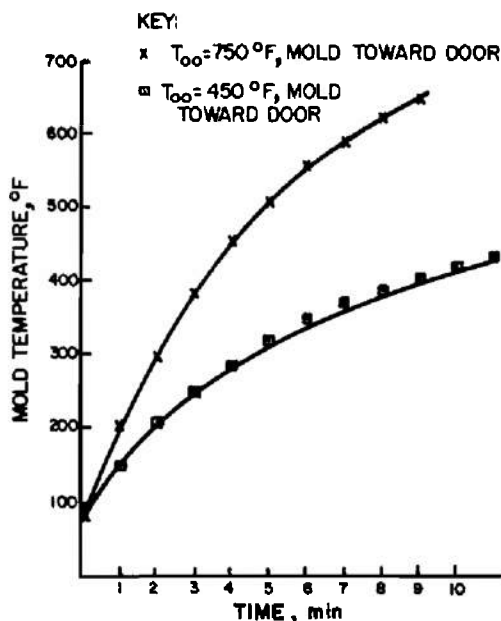
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Figure 4-4. Transient Temperatures of Mold Surface[2]

$$T = T_\infty [1 - \exp(-\beta t)] \qquad (4\text{-}1)$$

where

β = time constant for the mold

T_∞ = point temperature

This equation fits the data on Fig. 4-4 well if $\beta = 0.202$ min^{-1} and t is time in minutes. This time constant should be dependent on some measure of the heat capacity of the mold and the value of heat transfer coefficient in the forced air oven. A simple heat balance on the mold was made:

(The change in internal = (The net heat flow
energy of the mold   into the mold from
during time dt)   the environment
                                    during time dt)

$$T = T_\infty \left\{ 1 - \exp[-t(h\alpha)/Lk] \right\} \qquad (4\text{-}2)$$

where

h = heat transfer coefficient, Btu/ft^2-hr-°F

α = thermal diffusivity, $k/(\rho c)$, of the mold, ft^2/hr

Figure 4-3. Effect of Oven Temperature and Air Circulation Rate on Oven Cycle Time vs Resin Wall Thickness[5] (Based on Du Pont ALATHON® 7040 High-density Polyethylene Resin)

ρ = density of the mold, lb/ft^3

c = specific heat of the mold, $Btu/lb\text{-}°F$

k = thermal conductivity of the mold, $Btu/ft^2\text{-}hr\text{-}(°F/ft)$

L = mold wall thickness, ft

Rearrangement of Eq. 4-2 and integration yields

$$\frac{T_\infty - T}{T_\infty - T_o} = \exp[-t(h\alpha)/(Lk)] \qquad (4\text{-}3)$$

By comparing β from Eq. 4-1 and $(h\alpha/Lk)$ from Eq. 4-2 we find that the average heat transfer coefficient for the aluminum system is $h = 5$ $Btu/ft^2\text{-}hr\text{-}°F$. This is typical of forced hot-air coefficients. To achieve this rate of mold heating for other mold materials, it is necessary to change the wall thickness in accordance with Table 4-4.

Changing materials and wall thickness will influence the rate of mold heating; however, it is also possible to change the heat transfer coefficient h and the set point temperature of the oven T_∞. Increasing the heat transfer coefficient, thus decreasing the oven cycle time, has been achieved in commercial equipment through the use of hot oils. Kraus-Maffei is one such piece of equipment[6].

The effect of mold heat capacity and oven temperature on oven cycle time for various resin wall thicknesses for 1/8 in. nickel and 1/4 in. aluminum molds is illustrated in Fig. 4-5. The nickel mold had an induction time which was 75 percent and 85 percent that of aluminum at 400° and 600°F, respectively[5].

Mold surface to volume ratio, another measure of wall thickness, was investigated in the range 1/1 to 3/1 $in.^1$. No appreciable effect was found between 2/1 and 3/1 $in.^1$. Also higher temperatures appeared to dampen the effect somewhat. Both the effects of surface to volume ratio and oven tempera-
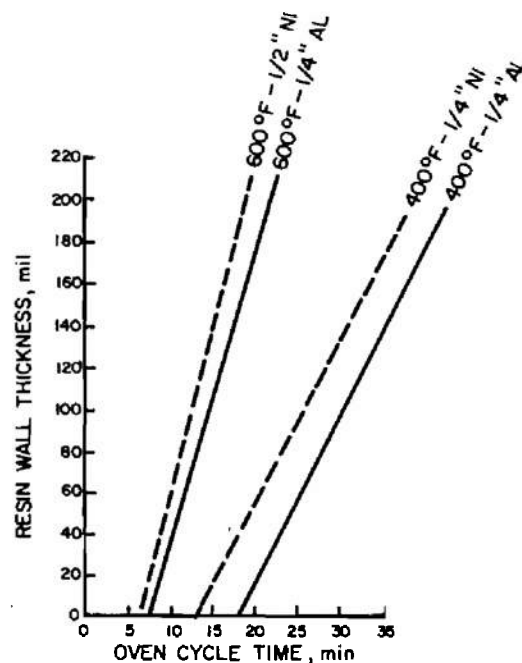
Figure 4-5. Effect of Mold Heat Capacity and Oven Temperature on Oven Cycle Time vs Resin Wall Thickness[5]

(Based on Du Pont ALATHON® 7040 High-density Polyethylene Resin)

tures are shown in Fig. 4-6. Most large molds used in rotomolding have a surface to volume ratio in the range of 0.8 to 0.4 $in.^{-1}$ (Ref. 5).

4-6.3 HEAT TRANSFER TO POWDER

The rate of heat transfer to the powder is directly proportional to the square root of the thermal diffusivity. Rao and Throne have developed a model for heat transfer based upon a simple cylindrical mold[2,7]. An assumption was made that the powder in contact with the cylinder moved with the cylinder, and, upon reaching a 50-deg dynamic angle of repose with the horizontal, released from the mold and fell across the remaining static powder in free fall. This is shown schematically in Fig. 4-7. Once the material becomes tacky and sticks to the mold surface, it is considered removed from the powder mass balance.

TABLE 4-4

MOLD MATERIAL DIMENSIONS NECESSARY TO MAINTAIN FIRST ORDER TIME CONSTANT OF 0.202 min^{-1} (Ref. 2)

MATERIAL	THERMAL DIFFUSIVITY α, ft^2/hr (500°F)	THERMAL CONDUCTIVITY k, BTU/FT^2-hr (°F/ft) (572°F)	α/k	WALL THICKNESS L, in.	$L/L_{aluminum}$
Aluminum	3.33	133	2.5 $\times 10^{-2}$	0.125	1
Copper	4.42	212	2.08 $\times 10^{-2}$	0.104	0.833
Nickel	0.60	32	1.88 $\times 10^{-2}$	0.094	0.751
Steel	0.49	25	1.96 $\times 10^{-2}$	0.098	0.785

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The equation that describes heat transfer during the contact period is given as

$$\alpha_{eff}\left(\frac{\partial^2 T}{\partial x^2}\right) = \frac{\partial T}{\partial t} \qquad (4\text{-}4)$$

where

T = mold temperature, °F

x = distance from the initial powder contact with the mold surface, ft

α_{eff} = effective powder thermal diffusivity, ft^2/hr

t = time, hr

Using the mold temperature given in Eq. 4-1, a temperature profile for the powder is obtained

$$T = T_\infty [1-\exp(-\beta t)](1-x/\delta)^3 \qquad (4\text{-}5)$$

where δ is the distance into the powder that the effects of the mold heat can be felt. δ is
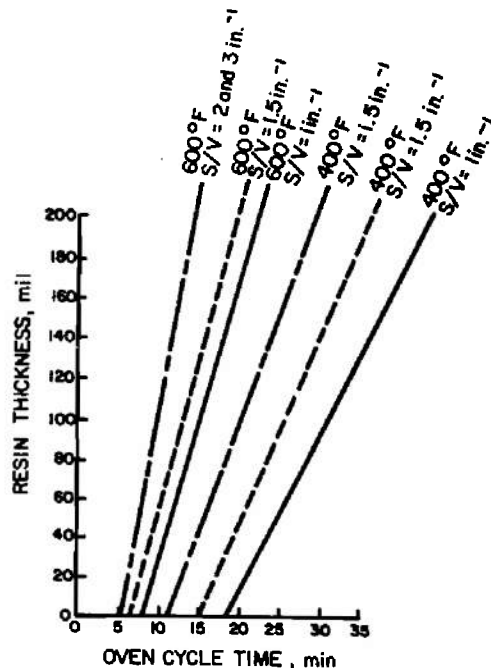
Figure 4-6. Effect of Mold Surface to Volume Ratio and Oven Temperature on Oven Cycle Time vs Resin Wall Thickness[5] (Based on Du Pont ALATHON® 7040 High-density Polyethylene Resin)
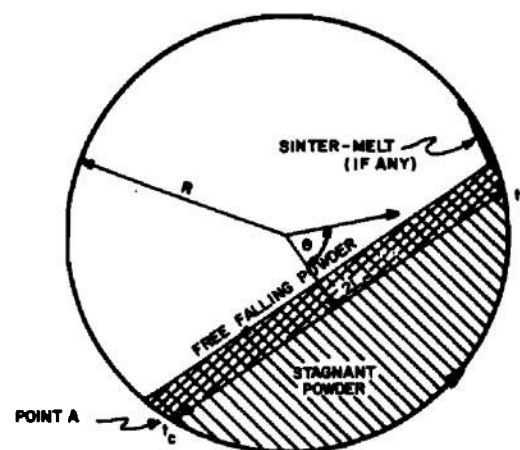
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Figure 4-7. Idealized Flow Configuration[2]

referred to as the penetration thickness. Following Goodman, it was found that the penetration thickness can be calculated from:

$$\delta = \frac{2\sqrt{6\alpha_{eff}}}{T_\infty(1 - e^{-\beta t_1}) + T^*}$$

$$\left\{ t_c \left[T_\infty^2 + 2T_\infty T^* + (T^*)^2\right] \right.$$

$$+ \left[\frac{2T_\infty^2}{\beta} + \frac{2T_\infty T^*}{\beta}\right] \left(e^{-\beta t_2} - e^{-\beta t_1}\right)$$

$$\left. - \frac{T_\infty^2}{2\beta}\left(e^{-2\beta t_2} - e^{-2\beta t_1}\right) \right\}^{\frac{1}{2}} \quad (4-6)$$

where

T^* = initial mold temperature

t_c = total time that the powder is in contact with the mold surface

t_1 and t_2 = initial and final times of contact, respectively.

Note that $t_c = t_2 - t_1$.

The time t_m required for the powder to fall from the point of release to the bottom of the cylinder is given as

$$t_m = [2L_c/(g \cos \beta_1)]^{\frac{1}{2}} \quad (4-7)$$

where

L_c = chord length

g = gravitational constant

β_1 = dynamic angle of repose

The method of calculation of time-temperature profiles is thus very straightforward, although some bookkeeping is necessary. At time $t = 0$, the powder is tracked at the point of contact until it releases. By knowing the rpm of the cylinder, the contact time t_c is calculated. At this time Eq. 4-5 and the integral of Eq. 4-5 are used to calculate the average powder temperature (assuming no melting). The time t_m required for the

powder to fall back in free fall and recontact the mold is given by Eq. 4-7. The new conditions for time $t = t_m + t_c$ are set and recalculated. The initial mold temperature T^* is obtained at this time from Eq. 4-1. When sinter-melting occurs, the melted material is removed from the powder that is releasing and freely falling, the chord length is adjusted as well as the free fall time (since there is less powder), and recalculations are made. Eventually $L_c \simeq 0$ and the process is stopped.

The major parameters evident in this analysis are the rpm, the melt temperature T_M the set point temperature T_∞, and the initial chord length L_c. The magnitude of the initial chord length determines the final part wall thickness. A typical time-temperature profile for $T_\infty = 750°F$ and $T_M = 300°F$ for two values of rpm (1 and 10) is shown in Fig. 4-8. The large effect of rpm on the temperature profiles is shown. The effect of T_∞ on the final melting time for $T_M = 200°F$ for various rpm's is similarly illustrated in Fig. 4-9.

Fig. 4-10 compares the predicted extent of melting with experimental values obtained by rotationally molding low density polyethylene at $T_\infty = 673°F$ in the aluminum mold with 1/8-in. walls, followed by immediate water quenching. The data seem to agree with the predictions using the penetration model described previously.

The OCT's calculated here are for complete pickup of powder onto the mold surface. That is assuming that all the powder has attained a temperature equal to or greater than the melt temperature. It is not assumed that the product is a homogeneous solid. On the contrary, at this stage, the material is called a sinter-melt. It is a porous three-dimensional network and the physical properties (such as density and thermal diffusivity) are about the same as the unsintered free flowing powder. Thus, the model developed for heat transfer to powder in a rotating geometry is adequate for predictions of oven cycle times for thin wall parts.
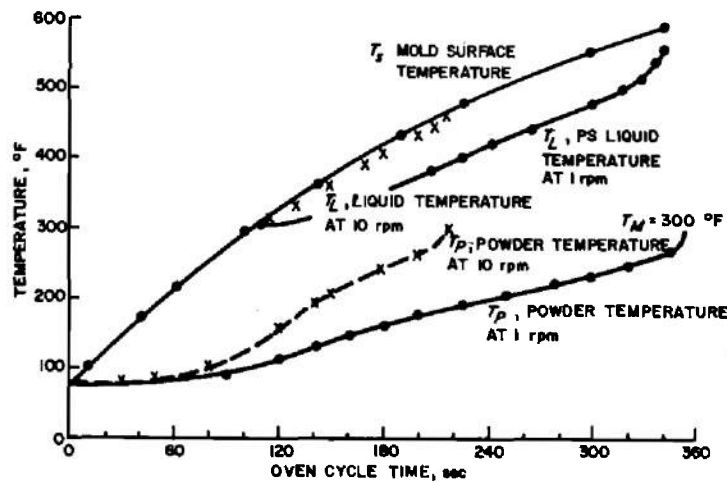
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Figure 4-8. Temperatures of Powder and Sinter-melt During Rotational Molding[2]

4-6.4 SINTER-MELTING

Upon continued heating of the sinter, the network begins to collapse into the void spaces. These void spaces are filled with molten polymer that is drawn into the region by capillary force in much the same way as

very small corners or capillaries are filled (see Chapter 6). This is called "densification". A polymer material that has only been sintered is quite porous and friable. One that has not been fully densified has low tensile strength, high surface porosity, rough interior surfaces, and interior bubbles or voids.

There are two models for sintering: The Kuczynski-Neuville viscous model that is an extension of glass sintering, and the Lontz
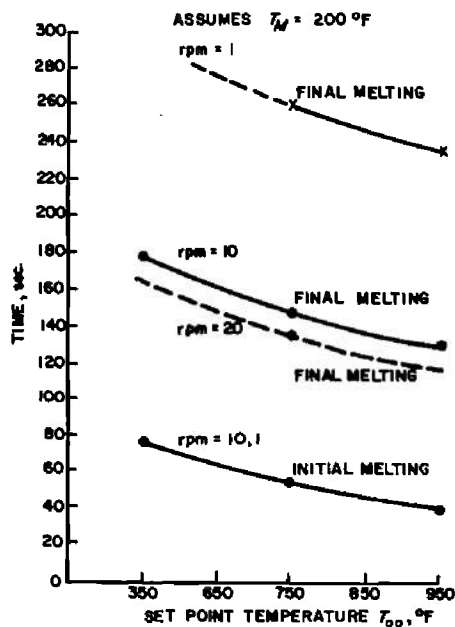
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Figure 4-9. Effect of Set Point Temperature T_∞ on Times of Initial and Final Melting[2]
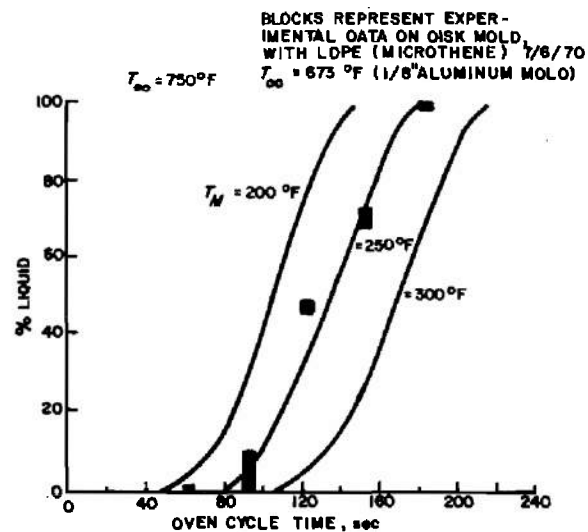
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Figure 4-10. Effect of Melt Temperature on Extent of Melting for $T_\infty = 750°F$[2]

viscoelastic model that relies on a four element spring dashpot model 8. In the former model, the growth of the web between two particles is controlled by reduction of free energy through decrease in total surface. Thus

$$(x/a)^2 = \frac{3}{2}\left(\frac{\gamma t}{a\eta}\right) \qquad (4\text{-}8)$$

where

x = web thickness, cm

a = particle radius, cm

γ = polymer surface tension, dyne/cm

η = polymer dynamic viscosity; poise, i.e., dyne-sec/cm^2

t = time, sec

For acrylic polymers, Kuczynski and Neuville found experimentally that

$$(x/a^{3/5})^{\eta} = K(T)t \qquad (4\text{-}9)$$

fit the isothermal data. Rao and Throne modified this expression to handle linear and exponential time-temperature profiles[9]. The linear profile describes transient heating of a Fischer Autemp hot plate, and the exponential profile describes the mold transient heating profile, Eq. 4-1. In Fig. 4-11, the calculated results are compared with experimental results obtained by heating polystyrene powder on the hot plate for a predetermined time, then quenching and measuring x/a values through a 100X optical microscope. Although the data seem to agree with the Kuczynski-Neuville model, it was somewhat fortuitous. Rao and Throne did not modify either surface tension or viscosity values in the adaption of the Kuczynski-Neuville model and the powder particles were irregular in shape rather than the spherical particles used by Kuczynski and Neuville. In addition, this model cannot account for the sintering behavior of acrylonitrile butadiene
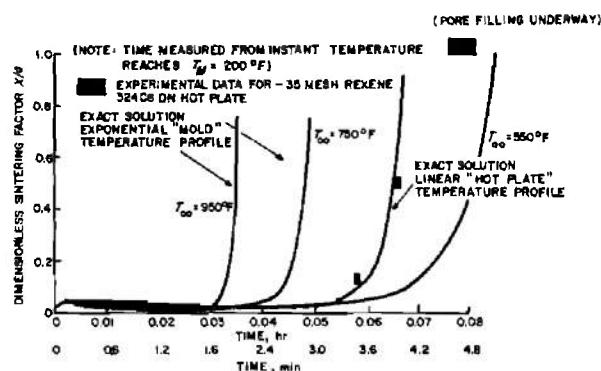
Figure 4-11. Kuczynski-Neuville Empirical Rate of Sintering[2]

styrene (ABS), high-impact polystyrene, or TFE Teflon®. Although webs are readily formed in these materials, complete sintering (x/a values greater than 0.5) requires abnormally long times[9].

The Lontz viscoelastic model replaces the standard Newtonian viscosity in Eq. 4-8 with a viscoelastic viscosity.

$$(x/a)^2 = \frac{3}{2}\left\{\frac{\gamma t}{a\eta[1-\exp(-t/\tau)]}\right\} \qquad (4\text{-}10)$$

where

τ = retardation time

Values for this time can be obtained from simple viscoelastic relaxation rate or creep rate data. For polystyrene, however, little data are available. Rao and Throne found that

$$\tau = \eta^{5/4} \times 10^{-9} \text{ sec} \qquad (4\text{-}11)$$

seemed to fit some creep data. The results for the linear and exponential time-temperature profiles are shown in Fig. 4-12, along with
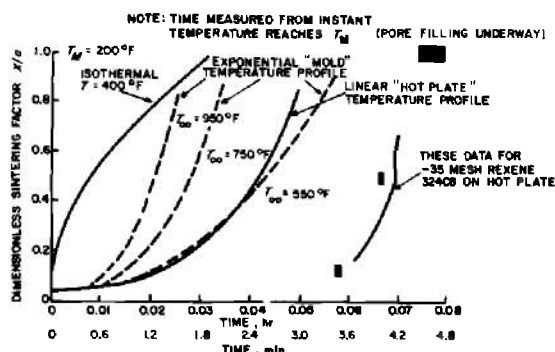
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Figure 4-12. Lontz Viscoelastic Rate of Sintering[2]

experimental data. For this material (assuming that property values are correct), the viscoelastic model predicts a much more rapid sintering rate than either that of the viscous model or the experimental data. The choice of the proper model to use will depend, of course, on the availability of physical property data and on experimental results obtained from simple hot plate experiments. It is not of concern which method of prediction is chosen—what is more important is that a realistic method for estimating sintering times is available.

Once the web-to-particle radius exceeds 0.5 or so, it was assumed that pores or voids will begin to fill with melt from below. Voids become bubbles. If melting or densification is relatively slow, the bubbles will be pushed ahead of the advancing melt front until they reach the free surface. If melting is relatively rapid, the bubbles are encapsulated and remain in the polymer after it is quenched[9]. Frenckel developed a theory of densification of glass that can be used here.

$$\left(1 - \frac{r}{r_o}\right) = \frac{\gamma t}{2 r_o \eta} \qquad (4\text{-}12)$$

where

r = instantaneous void radius, cm

r_o = initial void radius, cm

By applying the temperature at which sintering is said to be complete ($x/a = 0.5$), it was found that densification of voids initially of 450 μ in diameter to 0.45 μ in diameter finally takes less than a minute[2].

4-7 POLYMER MELT FLOW

According to Rao and Throne[10] the liquid viscosities of most plastics that have been evaluated as possible rotational molding materials are 10^2-10^5 poise in the normal processing temperature ranges. This high viscous range, coupled with the low speeds of rotation, implies laminar fluid flow. Furthermore, the shear rates encountered in rotational molding are very low. Thus they consider the values for the viscosities of these materials to be in the low-shear or zero-shear Newtonian region. Assuming that there is no appreciable increase in gravitational acceleration owing to rotation, the maximum shear stress on the fluid can be calculated. This corresponds to fluid flowing down a vertical wall.

$$\tau_w = \rho g \delta, \text{dyne/cm}^2 \qquad (4\text{-}13)$$

where

τ_w = shear stress at wall, dyne/cm^2

ρ = fluid density, gram/cm^3

g = acceleration due to gravity, cm/sec^2

δ = fluid film thickness, cm

Using polystyrene as an example, the investigators found that the zero-shear Newtonian viscosity is approximately 3 X 10^5 poise at 186°C. This yields a shear stress of 250 dyne/cm^2 for a 0.100 in. thick polymer film and a corresponding shear rate of 8 X 10^{-4} dyne (cm sec)$^{-1}$. The velocity profile

4-14

through the film layer was calculated using this information. The purpose of this calculation was to determine the maximum rate of movement of the polymer during conventional molding times. If the rate of movement was very large, considerable bulk flow throughout the mold cavity during molding would occur and thus significant flow into and out of portions of the mold having large aspect ratios. This high rate of flow would insure uniform wetting and coating of all mold surfaces. If, on the other hand, the rate of movement was very small, very little redistribution owing to fluid flow would occur. Thus mold surface coating would occur primarily by powder flow. Sinter-melting would thus freeze the plastic into the final configuration.

By use of the mold time-temperature profile given as Eq. 4-1, an Arrhenius form for the viscosity-temperature relationship (where the activation energy for polystyrene is 22.6 kcal/mol), and an oven set point temperature of 750°F, it was found that the differential velocity between the liquid at the mold surface and that 0.100 in. into the liquid was approximately 0.100 in. per second. This is approximately 2 percent of the angular velocity of the rotating 12-in. diameter cylinder mold. Therefore, they concluded that, contrary to the belief that voids in narrow passages are filled or emptied by molten polymer flowing into or out of the passages, the molten polymer exhibits very little fluid motion relative to the mold surface. Thus fluid does not flow by rotation induced forces into or out of passages[10].

4-8 MOLD RELEASES

The polymer melt in contact with the mold surface has the same velocity as the mold surface[2]. Thus the melt-solid-gas interface is interpreted as being essentially at equilibrium. The concept of contact angle discussed in par. 4-6.3 also applies here. The contact angle θ between a drop of a liquid and a plane solid surface is shown in Fig. 4-13. When

1. $\theta > 0$ deg, the liquid does not spread and when

2. $\theta = 0$ deg, the liquid spreads on the surface, the rate of spreading depends on the viscosity and surface roughness[11].

In practice every liquid wets every solid ($\theta \neq 180$ deg). The contact angle can be used as an inverse measure of spreadability and cos θ can be used as a direct measure. It can be shown[11] that the apparent contact angle θ' between the liquid and the solid surface, and the true contact angle θ (smooth solid surface) are related to a surface roughness factor r where

$$r = \frac{\text{true area of the solid}}{\text{apparent area of the solid}}$$

by the relationship

$$r = \frac{\cos \theta'}{\cos \theta} \qquad (4\text{-}14)$$

Eq. 4-14 is known as the Wenzel equation. Because r is always greater than unity (θ' is

A DROP ON A HORIZONTAL PLANE ; θ IS THE CONTACT ANGLE
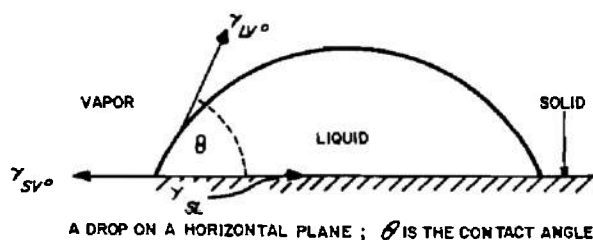
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Figure 4-13. Schematic of Drop on Horizontal Plane Showing Equilibrium Contact Angle (γ_{SL} = solid-liquid interface, $\gamma_{LV}°$ = liquid-vapor interface, $\gamma_{SV}°$ = solid-vapor interface)[2]

less than θ), surface roughness would tend to increase the spreadability. However, the roughness of the surface could lead to voids in the case of highly viscous liquids such as polymer melts.

The role played by mold release agents can be best understood by considering the concept of critical surface tension of wetting developed by Zisman and his co-workers. The concept of critical surface tension is described in many review articles[1,2].

"For a variety of liquids on a given solid, Zisman and his workers plotted $\cos \theta$ against the surface tension γ. The graphical points were found close to a straight line. The intercept of the line at $\cos \theta = 1$ is defined as the critical surface tension γ_c of the solid. Generally, the mold release agent has a low value of γ_c. The contact angle θ will be larger as the difference between γ of the liquid and γ_c increases. The large value of θ results in very poor adhesion of the liquid to the surface coated with the mold release agent, such that modest external force is sufficient for effective mold release"[2]. A mold release agent converts a high energy metallic surface to a low energy surface, and a monolayer of the release is enough to produce a low energy surface. Typical release materials are high molecular weight amines, amides, alcohols, fatty acids, polymethyl siloxanes, and Teflon®.

"The large value of the contact angle θ results in poor wetting of the solid by the polymer melt. Therefore, in corners or narrow passages that are hard to fill (with surface tension generated driving force) the use of mold release agents would in no way help the flow of the polymer melt; instead, they would be detrimental"[2]. Rao and Throne's experience with a mold having many sharp corners has shown that the voids at the corners increased in number when mold release agents were employed.

"Frequently, internal mold release agents, i.e., mold release agents which are part of the polymer powder, are also employed. Among the desired properties for an internal mold release agent is that it be surface active, so that it accumulates as an absorbed film on the solid surface"[12].

It is emphasized here that the concept of critical surface tension is purely empirical. However, the concept of γ_c has proved useful for characterizing the wetting and adhesion and the role of mold releases[2].

4-9 SURFACE POROSITY

Surface porosity is intrinsic to rotational molding. Unlike air voids which can be eliminated or minimized by judicious adjustment of the time and temperature of the polymer during the densification process, surface porosity cannot. Rao and Throne have reported that after much work with various materials and various mold surfaces, mold releases, particle size distributions and external lubricants, these pores were attributable to the sintering process itself. "The reasoning is as follows: Given the proper operating conditions, the voids in the bulk of the sintering powder are pushed ahead of the melting front as it proceeds toward the free surface. These hydrodynamic forces are sufficient to overcome viscous drag of the bubbles. Buoyant forces are relatively insignificant when compared with these forces. For the void on the mold surface, however, there is no bulk motion. As a result, buoyant forces must be sufficiently strong to counteract the viscous drag forces and the vertical component of the surface tension force that holds the bubble against the mold surface"[10]. By balancing the surface tension force against the buoyant force (assuming that the latter always acts in such a way as to release the bubble from the surface), it was found that the relative magnitudes of these forces are dependent on the geometrical parameters of bubble radius and area of bubble contact with the mold surface, and on physical properties such as density, surface tension, and the contact angle that the bubble makes with the liquid surface.

They reported that for polystyrene when the bubble is nearly detached (the excluded segment is 2 percent of the bubble radius) and the contact angle is extremely small (10 deg or so), and the bubble is under normal gravitational force, the minimum bubble radius for separation from the mold surface is 400 μ. "If the voids are formed in situ during the sinter-melting process, the void volumes should be of the same order of magnitude as the volume occupied by the powder particles. Thus for -35 to $+100$ mesh particles, the voids should be 100-500 μ in diameter (or 50-250 μ in radius)." These calculations, along with the visual observations, confirmed that the formation of voids is intrinsic to the rotational molding of plastic powder. "No mechanical or chemical means can be used to eliminate the voids, since, for most cases, the buoyant force is insufficient to overcome surface tension force and release the bubble from the mold surface"[10].

4-10 THERMAL DEGRADATION

Optimum cycle times are influenced to a large measure on the oven set point temperature. The temperature of polymer in direct contact with the mold surface is at or near the mold surface temperature, which, for high set point temperatures, can reach temperatures where significant degradation takes place. Materials such as acrylics, polystyrenes, and ABS are quite sensitive to excessive temperatures. Parts can exhibit discoloration, blisters possibly caused by gaseous degradation products, charring, and eventually combusted surfaces. Even if discoloration can be tolerated, excessive oxidative and thermal degradation lead to molecular weight reduction and decreased mechanical properties.

Rao and Throne examined the effect of excessive temperatures on final part properties of polystyrene. Plotted in Fig. 4-15 are data of tensile strength of rotational molded medium-impact polystyrene obtained at various OCT's and $T_\infty = 750°F$ (Ref. 9). To support these data, they examined the literature on isothermal degradation of

polystyrene in air. "Madorsky[13] reported that, upon exposure, the molecular weight of polystyrene decreases very rapidly to a rather stable molecular weight that is 10 to 100 times smaller in magnitude than the original molecular weight. This can be expressed as

$$MW(t) = MW(\infty)(1 + 6.70e^{-\beta_2 t}) \qquad (4\text{-}15)$$

where

$MW(t) =$ instantaneous peak molecular weight

$MW(\infty) =$ stablized peak molecular weight

$\beta_2 = 0.204$ min^{-1} for Madorsky's literature values"[9].

From Gel Permeability Chromatography (GPC) data on oven-exposed materials, it was found that the tensile strength of polystyrene was related to its molecular weight by

$$(\tau/\tau_o) = (MW/MW_o)^{1.4} \qquad (4\text{-}16)$$

where

τ = exposed tensile strength

τ_o = tensile strength of the unexposed polystyrene

MW = molecular weight of the exposed sample

$MW_o = 250,000$ (from GPC measurements)

By use of Eq. 4-16, the time-temperature profile for the mold, Eq. 4-1, and the molecular weight degradation Eq. 4-15, the curves shown on Fig. 4-14 for various set point temperatures were obtained. The agreement between theory and experiment was found to be satisfactory permitting the prediction of tensile strength with oven cycle times.

4-11 MOLD BLANKETING AND VENTING

Equipment through which inert gas and cooling media can be introduced into and
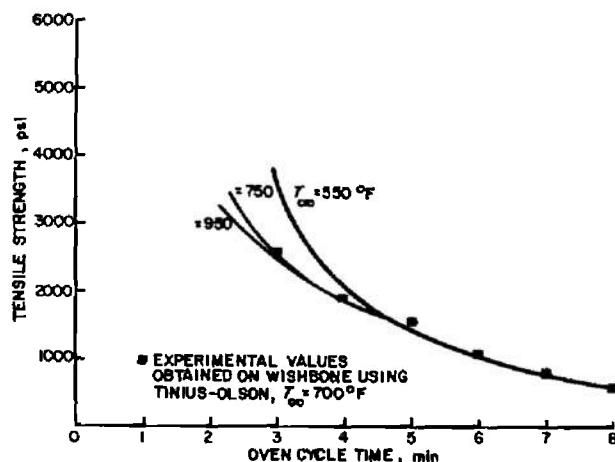
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Figure 4-14. Comparison of Computed and Measured Tensile Strengths of Polystyrene as Functions of the Oven Cycle Time[2]

vented from the mold during the heating and cooling cycles is recommended for rotational molding. Addition of inert gas purge can minimize some of the oxidative degradation from trapped oxygen in the mold; however, thermal degradation remains. Purging with dry ice (solid CO_2), argon, and nitrogen have been used with some success. Antioxidants also have been tried. However, it was reported that at 2 percent concentrations, 2, 6 diTertiaryButylpara-Cresol was ineffective in preventing tensile strength decrease at set point temperatures in excess of 700°F for polystyrene. This is probably due to the volatility of the antioxidant at these conditions[9].

Cool gases, water mist, or refrigerants have been introduced under slight pressure to reduce cooling times.

4-12 COOLING CYCLE

The cooling cycle can have a profound effect on the success or failure of the rotational molding operation. Improper cooling conditions and techniques can cause severe problems with warpage and some loss of physical properties. When unevenly cooled, the more highly crystalline polymers show a greater tendency to warp. Rapid cooling on the other hand can limit the growth of the

crystals and can slightly reduce the amount of crystallinity. Slow cooling promotes crystalline growth and may affect adversely impact strength. Therefore, very slow cooling should be avoided where possible.

Cooling of the molds generally is accomplished by cool air and/or spraying water over the molds while rotating. Since nonshocking uniform cooling is essential when molding warpage free parts, a detailed look at the spraying system is required. It has been found that the water spray rate, spray pattern, and spray particle size are three important variables to consider. Spraying the molds with a garden hose, as some people do, may occasionally work with some resins, but is seldom satisfactory for most parts. Changes in the cooling system will be required when polymers are changed.

Throne[14] has analyzed some of the factors that influence the rate of cooling of an amorphous plastic in a metal mold. To simplify the arithmetic, the following assumptions were made: (1) the inner surface of the mold has the same temperature as the outer surface, regardless of the metal wall thickness L and (2) the plastic part is quite thick when compared with the advancing "freezing" front. These assumptions enable the use of an

approximate method (known as the Goodman method[15]) to solve the transient heat conduction equation that describes heat transfer into the molten plastic.

4-12.1 MOLD HEAT TRANSFER

A heat balance is made for the mold material. At time $t = 0$, the mold, at an initial temperature of T_o, is moved into an environment at an ambient temperature T_a. The heat balance becomes:

(The change in internal energy of the mold during time dt) = (The net heat flow from the mold into the environment during time dt)

or

$$\rho_m \cdot c_{pm} \cdot L \cdot dT_s = h(T_s - T_a)dt, \quad \text{Btu/ft}^2 \quad (4-17)$$

where

c_{pm} = specific heat of the mold material, Btu/lb-°F

ρ_m = density of the mold material, lb/ft³

L = mold wall thickness, ft

k_m = mold thermal conductivity, Btu/ft² -hr-(°F/ft)

h = forced convection heat transfer coefficient, Btu/ft²-hr-°F

T_s = mold surface temperature, °F

Rearrangement and integration of Eq. 4-17 yields

$$(T_o - T_s) = (T_o - T_a)[1 - \exp(-\nu t)] \quad (4-18)$$

where

$\nu = [h\alpha_m/(k_m L)] \times (1/60)$, mold time constant, min⁻¹

$\alpha_m = k_m/(\rho_m c_{pm})$, mold thermal diffusivity, ft²/hr

This equation is a classic first-order system response to a step change in the environmental parameter.

This response is a strong function of the rate at which heat is removed from the mold surface, the thermal diffusivity and conductivity of the mold material, and the thickness of the mold wall. It is obvious that, for a given mold material, increasing the heat transfer coefficient or decreasing the wall thickness increases the rate at which the mold surface attains the ambient temperature.

4-12.2 THERMAL PENETRATION THICKNESS

The transient heat transfer equation that describes the temperature profile in the plastic melt is

$$\frac{\partial}{\partial x}\left(k_s\frac{\partial T}{\partial x}\right) = \rho_s c_{ps}\frac{\partial T}{\partial t} \quad (4-19)$$

where

k_s = thermal conductivity of the polymer, Btu/ft²-hr-(°F/ft)

ρ_s = polymer density, lb/ft³

c_{ps} = polymer specific heat, Btu/lb-°F

According to Goodman[15], the temperature profile in the polymer melt can be approximated by

$$(T_o - T) = (T_o - T_s)(1 - x/\delta)^3 \quad (4-20)$$

where

x = distance into the melt, measured from the mold surface

δ = thermal penetration thickness

This thickness is obtained by substituting Eq.

4-18 into Eq. 4-19 with appropriate boundary conditions. This is done in detail in Ref. 2. The form for $\delta(t)$, the penetration thickness, for a time-dependent surface temperature $T_s(t)$ is given as

$$\delta(t) = \frac{2\sqrt{6\alpha_s}}{(T_o - T_s)} \times \left[\int_0^t (T_o - T_s)^2 dt\right]^{1/2} \quad (4\text{-}21)$$

where

$\alpha_s = k_s/(\rho_s c_{p_s})$, polymer thermal diffusivity, ft^2/hr

The time-dependent mold surface temperature is given by Eq. 4-18. Substituting this into Eq. 4-21, the following expression for $\delta(t)$ is obtained

$$\delta(t) = 2L\sqrt{\frac{6\alpha_s}{(Bi)\alpha_m} \frac{1}{(1 - e^{-\nu t})}}$$
$$\times \left[\nu t - 2(1 - e^{-\nu t}) \right.$$
$$\left. + \frac{1}{2}(1 - e^{-2\nu t})\right]^{1/2} \quad (4\text{-}22)$$

where $Bi = hL/k_m$ the Biot number, representing the ratio of heat transfer resistance in the convective film of fluid next to the mold surface to the resistance to conduction heat transfer within the mold material. The penetration thickness is a strong function of the ratio of thermal diffusivities of mold and plastic.

Eq. 4-22 is rearranged slightly, introducing a dimensionless penetration thickness δ' that is a function only of the dimensionless time νt

$$\delta/L = K\delta' \quad (4\text{-}23)$$

where

$$K = 2[6Z/(Bi)]^{1/2}$$

$$Z = \alpha_s/\alpha_m$$

$$\delta' = (1 - e^{-\nu t})^{-1}\left[\nu t - 2(1 - e^{-\nu t}) \right.$$
$$\left. + \frac{1}{2}(1 - e^{-2\nu t})\right]^{1/2}$$

$\delta'(\nu t)$ is shown in Fig. 4-15.

(Note: Below $\nu t = 1$, the dimensionless penetration distance can be adequately approximated (within 10 percent) by $\delta' = (\nu t/3)^{1/2}$, and above $\nu t = 2.5$, by $\delta' = (\nu t - 1.5)^{1/2}$. These approximations are useful when calculating freezing conditions beyond the range of Fig. 4-16.)[14]

The extent of thermal penetration into the polymer melt can be determined by calculating $\delta(t)$ from Eq. 4-22. At any distance x, the temperature can be determined as a function of time by calculating $\delta(t)$ from Eq. 4-22 and $T(x)$ from Eq. 4-20. Further, if a "freezing" temperature T_f can be established such that $T_o > T_f > T_a$ the movement of the freezing front can be determined by rearranging Eq. 4-20:

$$x_f = \delta\left\{1 - [(T_o - T_f)/(T_o - T_s)]^{1/3}\right\} \quad (4\text{-}24)$$

where $(T_o - T_s)$ is given by Eq. 4-18 and δ is again given by Eq. 4-22.

This equation can be rearranged in a manner similar to that for the dimensionless penetration thickness $\delta'(\nu t)$. If $Q = (T_o - T_f)/(T_o - T_a)$, then Eq. 4-24 can be written as

$$x_f = KL\delta'(1 - Q^{1/3} e^{-\nu t/3}) \quad (4\text{-}25)$$

or, defining $x'(\nu t) = (x_f/L)/K$, $x'(\nu t)$ can be plotted as shown in Fig. 4-15 with Q as a parameter.
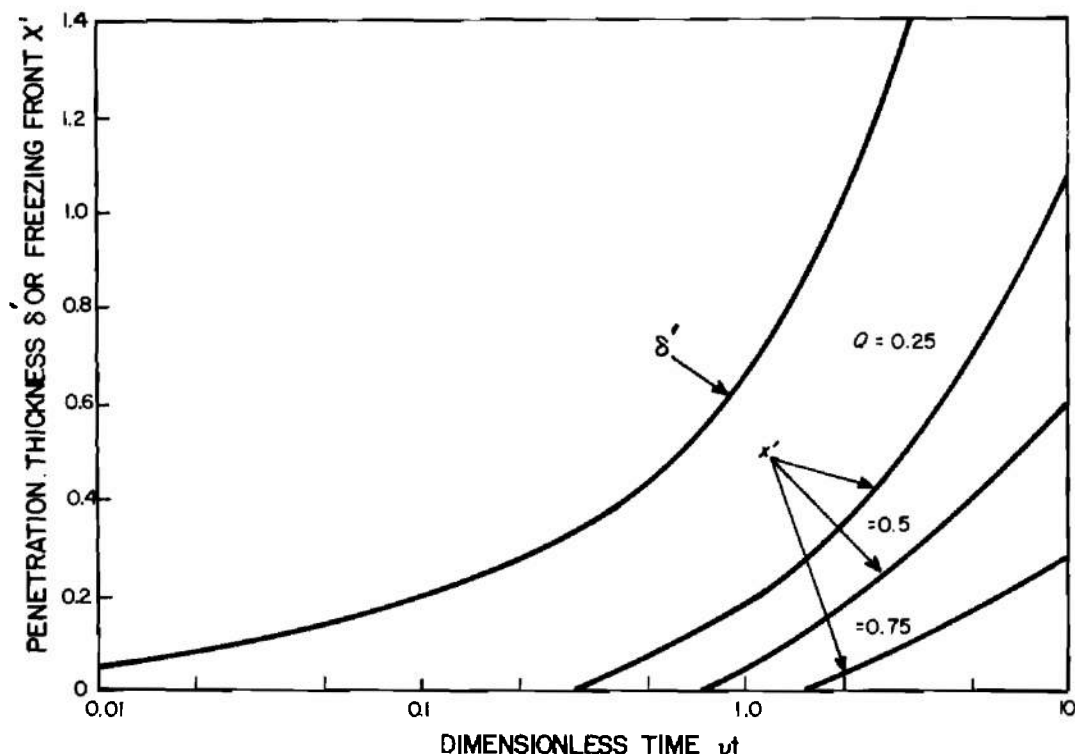
Figure 4-15. Dimensionless Penetration Thickness δ' and Dimensionless Freezing Front χ' as Functions of Dimensionless Time vt (Q,Dimensionless Freezing, is Parameter)[14]

4-12.3 VOLUMETRIC CHANGES

According to McKelvey[16], volumetric changes in amorphous materials such as polystyrene are functions of the rates of thermal cooling and the rates of viscous flow of chain segments. "McKelvey shows that the rate of volume change at any point in the material can be written as a total differential

$$dv/dt = (\partial v/\partial T)_t dT/dt + (\partial v/\partial t)_T \quad (4\text{-}26)$$

Spencer and Boyer[17] have shown that the instantaneous time-dependent volume change is directly proportional to the temperature change

$$(\partial v/\partial T)_t = b' \quad (4\text{-}27)$$

and that the isothermal rearrangement of chain segments can be described as

$$(\partial v/\partial t)_T = k' e^{-E/(R T)}(a + bT - v) \quad (4\text{-}28)$$

The rate of cooling dT/dt for conventional rotationally molded plastics in standard mold materials is extremely rapid when compared with the rate of chain segment rearrangement[14]. Thus Throne chose to neglect the effect of Eq. 4-28 on the time-dependent volumetric change of Eq. 4-26. This dramatically simplifies the form for the volumetric change, since now the volumetric changes are directly proportional to the temperature changes

$$dv/dt \doteq b' (dT/dt) \quad (4\text{-}29)$$

Further, any linear change in dimension is directly proportional to the cube root of the temperature change.

Differential changes in dimension are

4-21
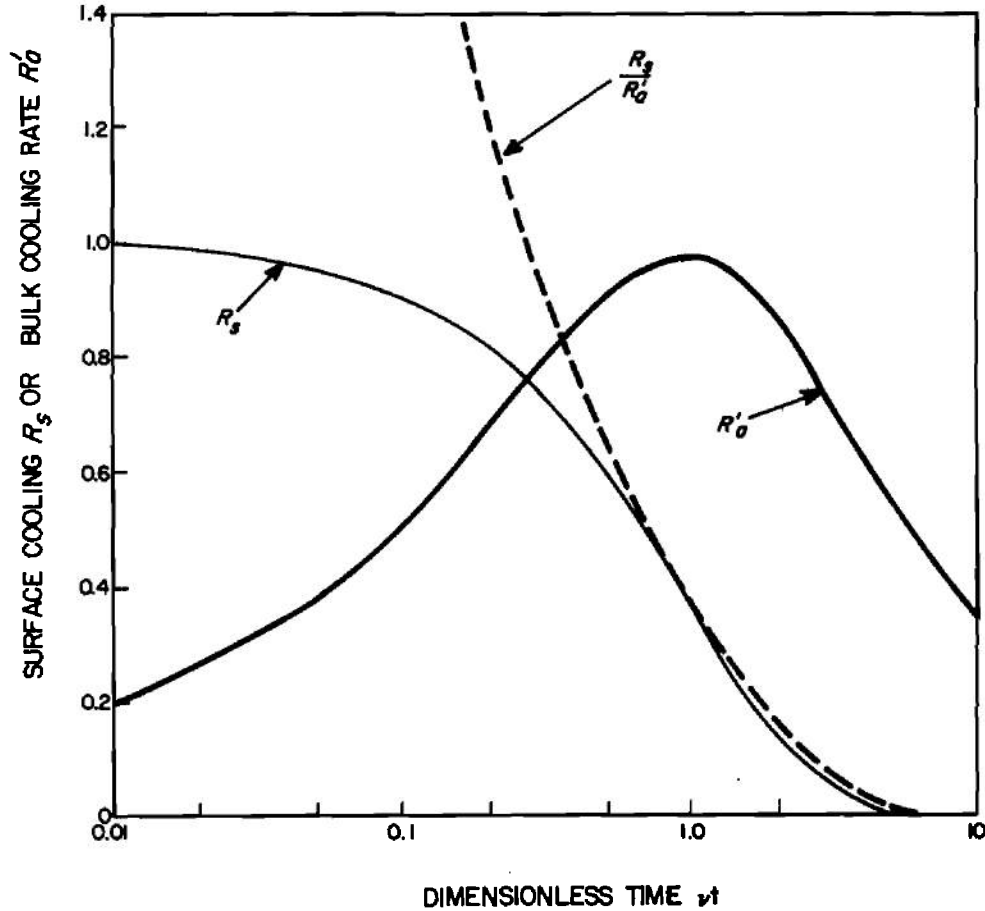
Figure 4-16. Surface Rate of Cooling R_s and Bulk Rate of Cooling R'_a as Functions of Dimensionless Time vt (Also Shown as Dotted Line is Cooling Rate Ratio)

considered more important than the absolute values of these changes. According to Throne a measure of this can be obtained by taking the ratio of the volumetric change of the material at the surface to that in the bulk.

$$\frac{(dv/dt)_s}{(dv/dt)_{avg}} = \frac{(dT_s/dt)}{(dT/dt)_{avg}} = \frac{R_s}{R_a} \qquad (4\text{-}30)$$

"The surface rate of cooling is obtained from Eq. 4-18 as

$$R_s = e^{-vt} \qquad (4\text{-}31)$$

and the bulk rate of cooling is obtained by differentiating the average temperature in the bulk. The average temperature is obtained as

$$(T_o - T)_{avg} = \int_0^\delta (T_o - T)dx \left(\int_0^\delta dx \right)^{-1} \quad (4\text{-}32)$$

or upon integration

$$(T_o - T)_{avg} = (T_o - T_s)\delta/4 \qquad (4\text{-}33)$$

and thus the bulk rate of cooling becomes

$$R_a = (1 - e^{-vt})/\delta = (K/4)R'_a \qquad (4\text{-}34)$$

where

$$R'_a = (1 - e^{-vt})/\delta' \qquad (4\text{-}35)$$

The surface rate of cooling R_s, the reduced bulk rate of cooling R'_a, and the ratio R_s/R'_a are shown in Fig. 4-16"[14].

Throne's analysis indicates that the temperature profile, the average temperature, and the position of the "freezing" front are strong functions of several parameters: $Z = \alpha_s/\alpha_m$, the ratio of the thermal diffusivities; $Bi = hL/k_m$, the dimensionless Biot number; $\nu = h\alpha_m/Lk_m$, a time constant for the mold response to a step change in environmental temperature; and $Q = (T_o - T_f)/(T_o - T_q)$, a dimensionless freezing temperature. All necessary physical constants are obtainable, and the heat transfer coefficient can be estimated for various cooling media. Thus a method is proposed by which methods of cooling and types of mold materials can be compared.

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CHAPTER 5

QUALITY CONTROL

5-1 GENERAL

Due to the cost of rotational molding equipment and the uncertainty about successfully processing a material of choice in a desired mold configuration, materials and mold designs should be screened before the decision to rotational mold is made.

5-2 POWDER SCREENING

Rao and Throne[1] outline several simple experiments that can be run which yield qualitative information about the rotational moldability of a plastic powder. These experiments can be run on inexpensive equipment and can serve as a screening procedure for materials.

5-2.1 "FEEL OR TEXTURE OF POWDER

A quick way of determining possible rotational molding problems is by allowing the powder to run through your hands. If the powder feels coarse, it may not have been ground fine enough. If the powder is dusty, the fines content may be too high. If it feels very slippery, this is an indication either that the particles are spherical in shape or that external lubricants have been used. Both of these can lead to molding problems. If it packs, it might be wet and might not cast properly. If it is very fluffy, the material may sinter properly but crack during densification. Furthermore, it may agglomerate during tumbling, owing to static electric charge build-up."[1].

5-2.2 MICROSCOPIC EXAMINATION OF POWDER PARTICLES

As discussed in Chapter 4, the ideal particle shape is cubic with generous radii, 35-100 mesh, and few fines. The shape of the particles can be quickly determined by 20 X microscope examination.

5-2.3 "PARTICLE SIZE DISTRIBUTION

Roto-tapping 300-500 g of powder through U.S. Standard sieves of 30, 50, 70, and 100 mesh for one to two hours yields particle size distribution data. Roto-tapping is preferred over manual methods because static electric charge build up easily can clog manually-operated screens."[1] This test is recommended on each batch of powder as a quality control of the grinding operation.

5-2.4 DYNAMIC ANGLE OF REPOSE

This can be determined with fair accuracy, simply by manually rotating the powders in a glass beaker or cylinder and estimating the angle with a hand-held protractor. The slip-stick phenomenon mentioned in Chapter 4 is more important to processing than the absolute value of the dynamic angle of repose. The more cubic or flat the particles become, the more they tend to alternately stick to and slip down the wall during rotation. This can be detected during manual rotation of the hand-held cylinder. Increasing sphericity or addition of external lubricants usually cause a dramatic visual reduction in this phenomenon. Slip-stick can also be caused by moisture adsorbed on the particles. If moisture is suspected, visual -comparison of oven-dried and wet materials in rotating cylinders should show a dramatic difference in flow behavior. A small variable-speed power-roller, such as that manufactured by U.S. Stoneware, can be used to good advantage here.

5-2.5 HOT PLATE EXPERIMENTS

It was found that a hot plate surface simulated, to a large extent, the mold surface for electro-deposited nickel and cast aluminum. The time-temperature profile was nearly linear throughout the useful temperature range ($<$ 600°F). The important fact, however, is that the profile is reproducible.

The hot plate can be used to determine an experimental value for the effective powder thermal diffusivity α_{eff}. While this is not an accurate method, it yields values which can be used in OCT calculations if no other is available.

Several visual effects can be observed while the powder is heating. First, the temperature at which the powder becomes tacky or sticky can be determined simply. The powder is moved across the mold surface with a probe until it sticks to the hot surface. The temperature at which this occurs is T_M. Secondly, a series of experiments, terminating at incremental temperatures, will give a good indication of the development of the sinter stage and of the progression of the melt stage through the sintered plastic. Microscopic examination of the cross section of the sample yields information on the extent of encapsulation of voids as a function of time. By controlling the rate of heating, a good indication of the effect of rate of densification on bubble encapsulation can be obtained. This test also can be used to determine whether a new material can be melted. For example, using this test Rao and Throne found early indications that increasing rubber content in ABS led to increased difficulty in densification. This problem was verified during rotational molding of the prototype part.

The extent of thermal degradation of certain temperature-sensitive plastics also can be observed using the hot plate. Flat disks, suitable for compression, flexure, or tensile testing, can be cast against the hot plate surface and physical property deterioration determined as a function of time and temperature. With an asbestos enclosure placed over the hot plate, inert gas purge can be used. Thus, physical property deterioration

as a function of time and temperature under CO_2, nitrogen, and argon atmospheres can be determined. Theoretically, the effect of thermal degradation could be separated from the effect of oxidation degradation.

5-3 PART QUALITY

Some tests which can be used for part quality control are percent gel, low temperature drop impact, density, resistance to stress cracking (Bent Strip), tensile strength, and elongation. These are in addition to visual observations for smooth, imperfection-free surfaces.

5-3.1 PERCENT GEL

The percent gel is a measure of the insoluble portion (gel) of the material in boiling ethyl benzene. The higher the percent gel, the higher the degree of cure. For example, to obtain optimum properties of crosslinked high-density polyethylene a percent gel above 95% is required. The test requires special equipment and takes 16 hr to run. It could be used to establish the initial time cycle and as a periodic check but would not be practical as a production control test[2].

5-3.2 IMPACT TESTS

A relatively small change in the heating cycle can make a significant difference in the impact strength. Laboratory tests have shown that the impact strength can be used as an effective method of determining when the maximum physical properties have been achieved.

"Impact testers such as the one shown in Fig. 5-1 can be built at low cost. This particular tester has a maximum drop height of 7.5 ft because of ceiling height limitations. Therefore, two different weight darts were necessary to obtain a sufficient range of impact values for testing parts up to 0.375 in. thickness. The 5-lb dart has a range of 0 to 37.5 ft-lb impact and the 10-lb dart has a range of 0 to 75 ft-lb impact. The dart has a 0.5 in. radius impact point and it strikes the part to be tested in the center of the 3.5 in.

diameter unsupported area. The support base could be removed and then whole molded parts could be impacted; however, care should be used to compare the results to parts impacted under the same condition. Results using the impact tester described in ASTM test D2444-70 with the 0.5 in. radius tip give very similar results, and it or other dart impact testers could be used to obtain the necessary impact data[3] ".

Using parts molded at increasing heating cycle times, an impact versus oven time curve can be developed. "From comparison of the impact curve and actual observation of the molded part, an optimum cycle time can be selected. This optimum cycle is the shortest cycle where the majority of the impact strength and physical properties are developed that are adequate for the intended application. The optimum cycle for some resins may be significantly shorter than the cycle needed for the maximum impact strength[3] ".

Low temperature impact tests also are used. To serve as any type of control the test must be run at least $-20°$F for crosslinked high-density polyethylene[2]. The impact can be run on a slab cut from the part or the part itself can be impacted. A simple 0.5 in. radius dart has been used to test slabs. The slabs are cooled to $-20°$F in a bath containing an alcohol-water solution and dry ice. In production, a ball peen hammer has been used for this test. With the dart or hammer, there should be no failure, or if failure does occur it should be ductile. If at $-20°$F a part will take a good swing with a 5-lb ball peen hammer, the part is probably good.

5-3.3 DENSITY

Density of the part can be used for quality control when rotomolding natural crosslinked polyethylene. For natural parts, a density between 0.930 and 0.933 g/cm^3 is necessary for optimum part quality. Density cannot be used for black or pigmented parts, since a very slight change in percentage of pigment could vary the density enough to make it misleading[2].
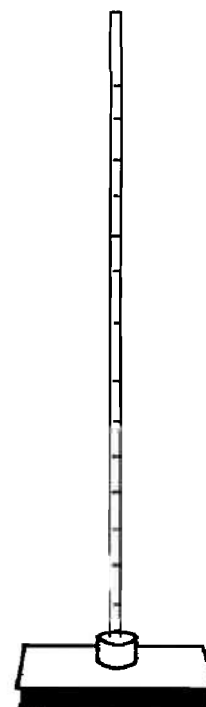
Figure 5-1. Dart Drop Impact Tester

5-3.4 BENT STRIP TEST

Another test which can be used as a means for quality control for crosslinked polyethylene is a Bent Strip Test. For this test a small strip approximately 0.5 in. X 4 in. is cut from the part. Any size 0.25 in. wide or greater which can be easily bent can be used. "The strip is bent such that the inside surface is exposed until the two ends meet. If cracks appear in the stressed area, the part is undercured. This indicates that the inside surface has not reached sufficient temperature to cure and a longer heating time is needed. Ideally, the inside surface when bent to give maximum stress should look like the outside surface when under maximum stress. When this occurs, the optimum properties of the resin have been obtained[2] ".

5-3.5 TENSILE TESTS

Tensile properties have been used widely

5-3

for determining production quality. Changes in tensile strength and elongation may be used to follow the progress of chemical or physical changes taking place in the polymer—such as densification, thermal or oxidation degradation or, in crosslinked polymer, degree of curing. Tensile properties also are used to determine uniformity of production. Generally, finished parts are difficult to test because of their geometry, and tensile testing is accomplished on standard test specimens using standard ASTM test procedures (i.e.,

D638, D1708, D1623, etc.). In some cases, however, specimens can be taken from some part of the finished part and some measure of the quality of the finished part determined. Tensile test procedures and properties are well documented in the open literature.

5-4 PROCESSING PROBLEMS

Table 5-1 presents some of the major rotational molding problems, their probable cause, and suggested remedies.

TABLE 5-1

ROTATIONAL MOLDING PROBLEMS AND PROBABLE SOLUTIONS[4]

PROBLEM	PROBABLE CAUSE	REMEDIES
Uneven wall thickness of molded part	Improper mold rotation	Correct rotation to get adequate number of powder overlays and even coverage.
	Uneven mold thickness	Use care in designing molds to eliminate excessive variations in mold wall thickness. This is especially important with steel molds that have low heat conductivity.
	Shielding of mold preventing hot air flow.	Mount mold on spider so as to minimize shielding.
	Buffeting of hot air flow in deep dished areas.	Avoid deep dished areas when possible.
		Reduce thickness of mold in dished areas.
		Open handles so that air can flow through kiss-off in mold.
Excessive oven cycle	Low oven temperature	Increase oven temperature.
		Check calibration of instruments as they may be reading high.
	Excessively thick molds	Reduce mold wall thickness to normal for industry.
	Oven heat capacity insufficient	Clean and readjust burners.
		Check air velocity and correct if low.

TABLE 5-1 (Continued)

ROTATIONAL MOLDING PROBLEMS AND PROBABLE SOLUTIONS[4]

PROBLEM	PROBABLE CAUSE	REMEDIES
Warped parts	Uneven cooling caused by resin pulling away from mold wall	Excessive or too effective a mold release
		Rotate during cooling cycle.
		Make sure mold is venting to prevent vacuum.
		Add air pressure through drilled spindle during cooling.
		Decrease cooling rate.
		Allow short air cooling before water cooling.
	Mold design	Improve wall uniformity of part.
Blow holes through part or ringworm effect under outer part wall surface — other than parting line	Porosity in cast aluminum mold	Obtain better quality castings.
		Drill through void and drive in pin or weld from inside.
		Relieve from outside by drilling into void from outside.
		Remove parts from molds while mold is quite warm to touch. This helps drive moisture out of pores.
	Pores or holes in welds	Use proper welding rod and procedure.
		Weld inside surface first to get good penetration.
Blow holes through part around inserts	Poor fit on inserts, allowing moisture or vapors to be trapped around insert and expand, blowing a hole in the part	Refit inserts and relieve, so as to allow trapped gases to escape to the outside of the mold.
	Bridging of resin because of close dimensions	Change insert dimensions or location to allow powder to flow without bridging.
Surface of part discolored	Surface oxidized	Flush mold with inert gas.
	Excessive heating cycle	Reduce oven time or temperature.
	Contaminated mold	Check mold wall for a contamination such as rust.
Speckled color and lumps of color in dry blended colors	Insufficient blending	Break up agglomerates of pigment before blending.
		Use high intensity mixer.
		If unable to achieve a desirable color balance, use a color compound.

TABLE 5-1 (Continued)

ROTATIONAL MOLDING PROBLEMS AND PROBABLE SOLUTIONS[4]

PROBLEM	PROBABLE CAUSE	REMEDIES
Pock marks with crosslinkable resin	Mold release	Change to a mold release that is satisfactory for crosslinkable resins.
	Too high oven temperature	Lower oven temperature to 600°F or lower
Delamination with crosslinkable resins	Improper rotation	Change speeds and/or rotation to give even coverage of mold.
Small bubbles and large blow holes at parting line	Vacuum inside part due to plugged vent or lack of vent	Install vent.
		Relocate vent to put end in middle of mold if possible.
		Use small amount of glass wool in vent.
		Use low conductivity material such as Teflon® resin for vent tube.
	Poor parting line	Clean parting line and apply new mold release on parting line.
		Remate parting line if necessary and check to see that adequate clamping force is evenly applied.
Excessive flash on parts	Poor parting line or mold mismatch	Clean parting line and apply new mold release on parting line.
		Remate parting line.
		Use lower melt index resin.
		Check vent for plugging.
		Reduce air pressure in part if used.
Sticking to mold	Lack of mold release agent	Reapply or use more release agent.
		In some cases, old release and film must be removed, and new mold release applied for good results.
	Ineffective mold release	Use mold release that is effective for resin and temperatures used.
	Shrinking onto large, deep inserted areas.	Provide adequate taper.
		Use very effective mold release on insert area.
		Remove part warm.
		Provide adequate provision for applying force to separate mold halves.
	Undercuts in mold	Design mold so that undercuts are at parting line so that mold has draft angle for part removal.
		Decrease heating cycle or oven temperature.
		Increase cooling cycle.
		Vent mold.
		Reduce cooling rate during initial part of cooling cycle.
		Reduce oven temperature.
		Avoid large flat panels when possible.

TABLE 5-1 (Continued)

ROTATIONAL MOLDING PROBLEMS AND PROBABLE SOLUTIONS[4]

PROBLEM	PROBABLE CAUSE	REMEDIES
Sticking to mold (cont'd)	Uneven cooling caused by shielding panels	Remove shielding panels and replace with screen if necessary.
	Uneven cooling caused by clogged water nozzles	Check and clean nozzles on a periodic schedule.
Low impact strength	Overfusion	Decrease cycle time.
	Insufficient fusion of resin	Increase time or temperature.
	Too slow cooling	Avoid excessive air cooling.
		Cool as rapidly as possible using techniques mentioned to prevent warpage.
	Improper coloring	Select pigment and pigment loading that do not materially affect impact strength.
		Use color compounds.
Bridging or webbing of resin across one wall to another, causing poor fill of narrow passages in mold	Poor mold design	Design corners of mold with more generous radii.
		Avoid ribs with width of less than 4 X wall thickness.
		Use higher melt index powder.
	Poor pourability of powder ground in plant or by custom operator	Make sure powder has acceptable pourability.
	Improper mold rotation	Correct ratio and speed of rotation
Part contains small bubbles or blisters in wall, has small bubbles that have ruptured on exterior surface, causing pin holes or has rough powdery inside surface	Water in mold	Reduce water in mold by running with warm molds and dry mold before charging with powder.
	Insufficient cycle time or molding temperature	Increase oven cycle.
		Increase oven temperature.
	Mold design	Use thinner wall on part. Improve mold wall uniformity.
Watermarks — glossy marks on otherwise dull surface	Water in mold interior	Redesign vents to prevent water from entering during cooling cycle.
		Use fog instead of water spray.
		Cool in air cycle.

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CHAPTER 6

PART DESIGN

6-1 GENERAL

A few of the part design parameters that should be given special considerations are flat surfaces, undercuts, threads, inserts, radii of corners, narrow passages, and composites.

6-2 FLAT SURFACES

Large flat surfaces can create warpage problems. If at all possible, parts should be
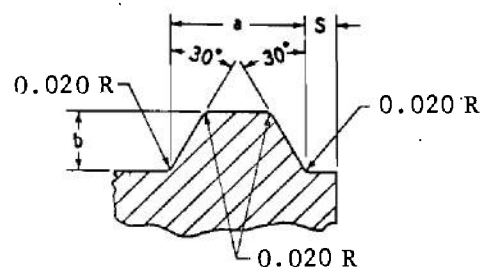
(A) ALL PURPOSE THREAD
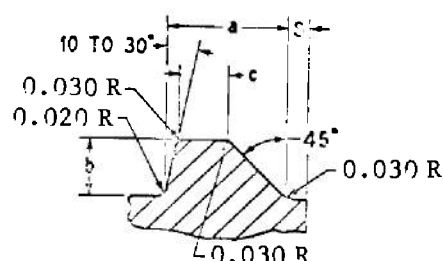
(B) MODIFIED BUTTRESS THREAD
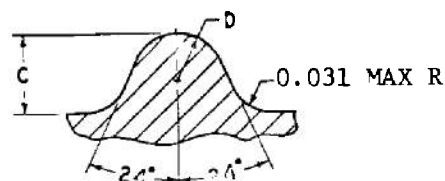
(C) ALTERNATE TYPE (GLASS)

Figure 6-1. Various Acceptable Thread Types for Use on Rotational Molded Parts[1]

designed to avoid flat sections and, where necessary, they should be broken up with either ribs or domes to hold warpage problems to a minimum.

6-3 UNDERCUTS

Undercuts should be held to a minimum in rigid parts. If undercuts are required, the mold should be parted to allow for easy part removal. Also, undercuts usually require additional time for loading and unloading the mold.

6-4 THREADS

"Threads should either be a round glass bottle or a modified buttress. The round glass bottle thread will fill well without any modification. For the buttress to fill and form properly, generous radii on the edges of the threads are required. Sharp V threads should be avoided, for powder tends to bridge causing very poor fill"[1]. The various types of threads are illustrated in Fig. 6-1.

To produce an internal thread, as shown in Fig. 6-2, rapid extraction (after a strictly limited cooling time) is usually necessary because the plastic material shrinks onto the core[2].

6-5 INSERTS

Metallic or plastic inserts of appropriate shape may be positioned into the mold before the addition of the resin by use of jigs or magnets. In this way inserts can be molded in a one shot operation. Such inserts can be used to fix outlets, filters, valves, etc., to a hollow

Thread mold insert

Thick base essential
to produce a thin wall

Inside mold

(A) Internal thread

(B) External thread
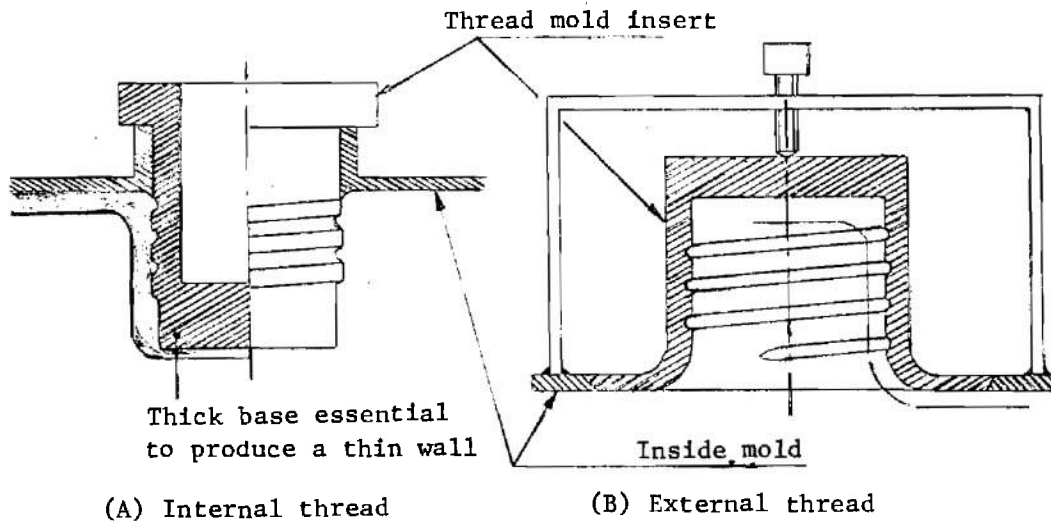
Figure 6-2. Thread Mold Inserts[2]

part. However, with metal inserts, care must be taken to minimize built-in stresses in the molded part due to differential shrinkage of the metal and the plastic. Inserts should be carefully degreased before they are inserted. Fig. 6-3 illustrates such an insert, and the method of attaching the piece to the mold.

Excellent results have been reported using Rilsan ZMO (30 percent glass-filled nylon 11) inserts, to which the nylon 11 rotomolding grade layer adheres well. The insert and its support are so designed that the flange, as

shown in Fig. 6-4, of the inserted piece melts sufficiently to produce perfect adherence to the nylon layer while the thickest central part of the insert support bears the thermal shock with no deformation of any sort[2].

Heterogeneous inserts (metal-plastic) made by normal injection molding (i.e., a metallic nut in a plastic surround) may also be used. The shape of such pieces is a function of the specific problem in hand.

Inserts held in the mold by bolts should not be placed far from other inserts in the

Interior of mold

Metallic insert

Retaining clip

Material

Supporting block
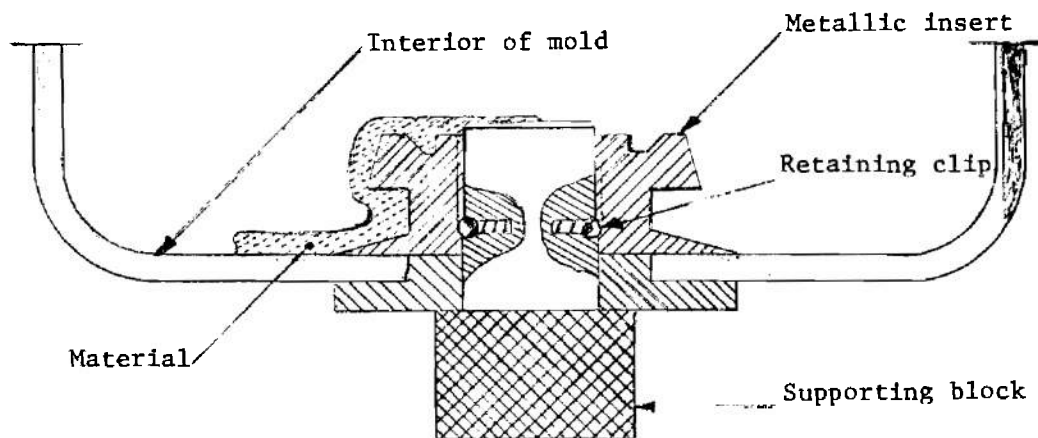
Figure 6-3. Metallic Insert[2]
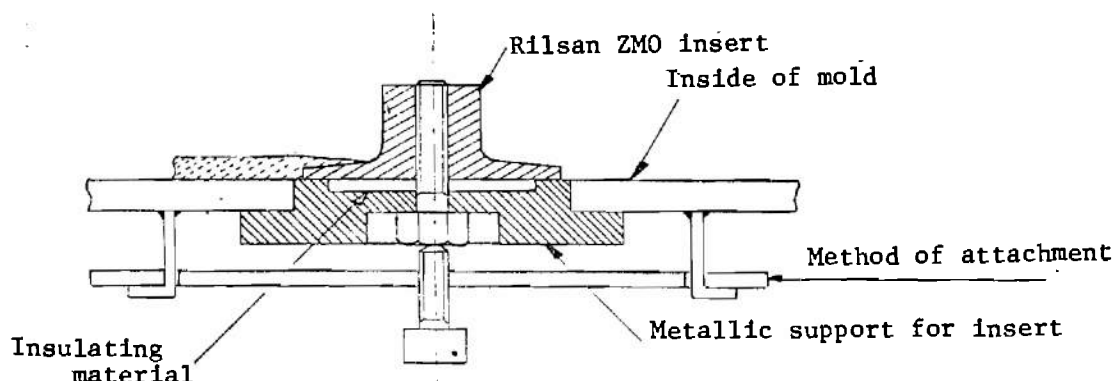
Figure 6-4. Rilsan ZMO Insert[2]

same part. This is because large shrinkage forces can be generated which will cause difficulty in removing the bolts that hold the inserts in place. It may be possible to use magnets or specially designed insert mountings in the mold to hold the inserts in place. In crosslinking resin systems the fastening of inserts in molds should be done in such a manner that gases or steam generated behind the inserts are relieved to the outside of the mold.

6-6 CORNER RADII

Well radiused corners are recommended to prevent molded-in stresses and part thickening in the corners. Normally, radii of at least 1/4 - 3/16 in. are required. See par. 2-3.6.

6-7 COMPOSITES

Multilayer products are possible which are formed by the juxtaposition of layers of thermoplastic materials of different nature but adhering together. Thus, it is possible to combine the specific properties of each of the materials used to produce a cheaper or better product, for example, replacing a certain thickness of an expensive material with the equivalent or greater thickness of a cheaper material.

Multilayer or sandwich composites are rotomolded by two basic methods:

1. Resin powders of two different melting temperatures are premixed and charged into the mold cavities. An example of such a technique is the familiar ice bucket which has a polystyrene core and a polyethylene skin.

2. The mold is charged with the required quantity of the first thermoplastic. After this layer is formed against the mold, the mold is opened and charged with the appropriate second resin. This is then rotomolded on top of the previous layer. If a solid skin with a honeycomb interior is required, a blowing agent is used in one of the powdered resins.

6-8 WALL THICKNESS

The wall thickness of molded parts is usually fairly constant. However, wall thicknesses can be varied by:

1. Adjusting the rotational ratio such that the powdered resin has more contact time with either the walls parallel to the major axis of rotation or the walls parallel to the minor axis of rotation. The increased contact time will produce thicker walls in these areas.

2. Either speeding up or slowing down heat transfer in the desired area. This can be accomplished by varying the wall thickness of the metal mold in the area of interest. Another technique is to paint a surface of the mold with black paint for thicker wall sections, or with aluminum paint for thinner wall sections. Also mold preheat in the areas requiring thicker wall sections is feasible.

Thicker mold walls for thinner resin wall sections should be used with care. The mold wall thickness should be increased with the least amount or no increase in the outside area of the mold. Otherwise, the resin build-up under this thicker section will be thinner than desired in short OCT but thicker in long OCT. This is because the increased mass of metal acts first as a heat sink and its temperature rises more slowly than the rest of the mold. Thus, the heat transfer time for the molding surface under this thicker section is longer than for the rest of the mold. During a long OCT, the thick section, with increased outside area, will act as a heat funnel. Then the molding area under this section will flux more heat into the polymer wall which is building on it. The lower limit of part wall thickness is approximately 0.05 to 0.06 in.

6-9 INNER COMMON WALLS

It is possible to have a hollow rotomolded body split into two chambers by a solid wall of resin. This can be accomplished by placing a screen mesh insert in the position where the inner wall is to occur. The screen must be affixed to the mold so that it will get enough heat to fuse the polymer. Under these conditions an inner wall can be built simultaneously with the rest of the molding. The screen insert, however, remains as an integral part of the molding.

6-10 PART SHRINKAGE

Part shrinkage is a very complex phenomenon and is also influenced in rotational molding by oven temperature, resin type, mold configuration restrictions, cooling rate,

part wall thickness and, to a substantial degree, by the mold release condition. Therefore, it is impossible to quote a specific value for each resin system for different designs. Linear shrinkage for parts molded in the laboratory and others from production has varied from 0.0125 in./in. to 0.025 in./in. for crosslinked polyethylene[1]. Indications of shrinkage are given in Chapter 7.

6-11 NARROW PASSAGES

Experimentation by Rao and Throne[3] have shown that, contrary to the belief that voids in narrow passages are filled or emptied by
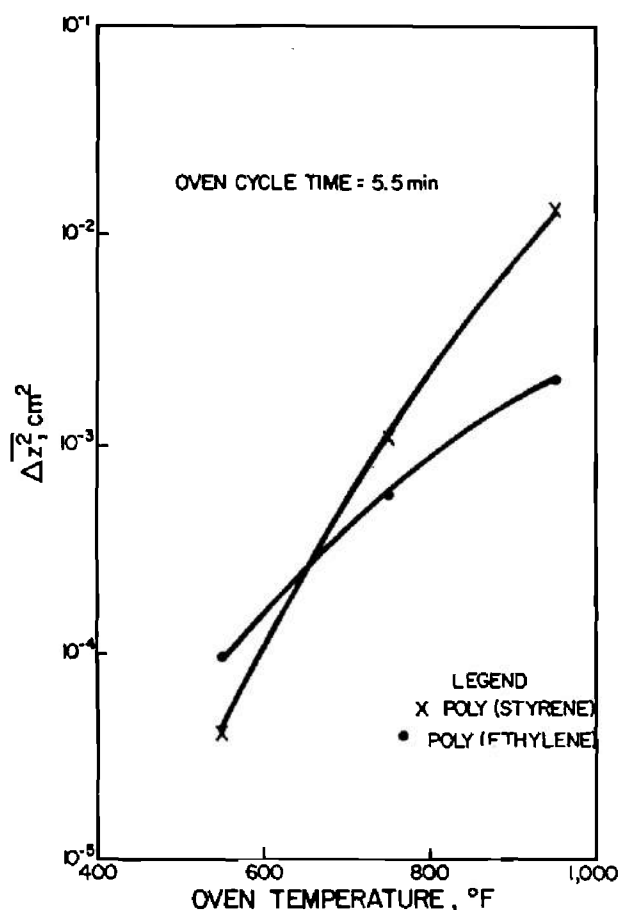
Figure 6-5. Capillary Flow Distance During OCT = 5.5 Min (Oven set point temperature is parameter. R = 0.01 cm (Ref. 3)).

molten polymer flowing into or out of the passages, the molten polymer exhibits very little fluid motion relative to the mold surface. "Thus fluid does not flow by rotation induced forces into or out of passages. This lack of complete filling results in voids and gaping holes. The main driving force for the flow of a viscous fluid into a narrow passage is surface tension." The maximum possible flow of a polymer in an axial direction in a horizontal capillary tube is given by

$$\Delta \bar{z}^2 = (\bar{z}_2^2 - \bar{z}_1^2) = \frac{R}{2} \int_{t_1}^{t_2} \frac{\gamma(t)}{\eta(t)} \, dt \quad (6\text{-}1)$$

The surface tension γ and viscosity η both decrease with increasing temperature. How-ever, the viscosity is exponentially dependent on temperature, whereas surface tension is linearly dependent. As shown in Fig. 6-5, the depth of capillary fill at a given OCT of 5.5 min dramatically increases with increasing set point temperature. Even so, the depths of capillary that can be filled with polystyrene at $T_\infty = 950°F$ after 5.5 min ($R = 0.01$) is only 0.100 cm long. Thus it is concluded that deep cavities cannot be filled successfully either by rotation, induced flow, or by capillary forces. This conclusion is, to a large extent, applicable to the filling of corners and areas of relatively sharp radii as well. Thus, designers must take this factor into account in the design of parts[3].

REFERENCES

1. "Technical Information on Marlex® Poly-olefin Plastics: 17 Rotational Molding", Phillips Petroleum Co.

2. "Rilsan GSMR (Special Grade for Rotational Moulding)", *Aquitaine-Organico*, No. 168, 1969.

3. M.A. Rao and J.L. Throne, "Theory of Rotational Molding—Part II: Fluid Flow", *Society of Plastics Engineers, 30th Annual Technical Conference*, May 1972, Chicago, Ill.

CHAPTER 7

MATERIALS

7-1 CRITERIA FOR SELECTION

The base resin selection is very important since it is the foundation of the process and must be selected to fit the performance of the product. In selecting a resin system the following end use requirements should be considered:

1. Strength requirements

2. Rigidity or flexibility

3. Temperature range part will be subjected to

4. Life requirement of the part

5. Indoor or outdoor use

6. Part surface requirements—texture or finishing acceptability

7. Color requirements

8. Special requirements, i.e., stress crack resistance, chemical resistance, FDA approval, etc.

These requirements will influence the resin selected as well as possible additives and fillers. Additives such as plasticizers, ultraviolet stabilizers, and flame retardants often are incorporated into the resin system depending on specific requirements. Glass reinforcements also are included to increase strength and impact properties.

When color is desired, pigments and concentration levels should be selected that will not affect resin strength properties.

Generally compounded color is superior to dry color in the rotomolding process.

Specific resin properties—i.e., melt index, density, tensile strength, elongation, low temperature brittleness, flexural stiffness, impact strength, heat distortion temperature, stress crack, and chemical resistance—and FDA approval must be considered in assessing the best resin system for product requirements.

Stress crack problems have been and are a source of concern because of part failures. They have occurred in fertilizer tanks, gasoline tanks for utility vehicles, and other containers where certain liquids have been confined. Recently, the resin producers have given this area special considerations, and several new resins have been developed to solve the problem. Unfortunately, they also cost more than the previously used materials. These new materials include polybutylene, crosslinked polyethylene, and special co-polymer modifications.

Improper part mounting is sometimes responsible for failures attributed to stress cracking. For example, a large fertilizer tank requires a full length cradle. If the tank is secured by bands, the bands should allow for expansion of the tank with rising temperature. Otherwise, the bands can exert sufficient stresses to possibly cause failure.

Rotational casting resins may be purchased from suppliers in the powder form. Some of the larger rotational molds have their own pulverizing facilities. Generally, a resin in powder form costs from $0.05 to $0.10 per lb more than the pellet form of the resin. On a

large volume operation, the molder can save by having his own grinder.

Other approaches to rotomolding parts with specific applications have developed. One has been to post-fill hollow rotomolded parts with rigid urethane foam in order to achieve additional strength and rigidity. This is particularly true in the application of rotomolded styrene in the furniture industry. The rigid foam reinforcement also changes the metallic ring of styrene to the dull sound of wood.

The field of powder molding materials has come a long way since liquid vinyl plastisol rotational casting. A summary of available materials as of this time is presented along with a general description gained from processing these materials and their properties. Because of rapid changes in the cost of resins only approximate costs are given.

7-2 ACETAL COPOLYMER

Acetal copolymers offer the rotational molder an excellent combination of strength, stiffness, solvent resistance, good fatigue, endurance and creep resistance, low moisture absorption, and good thermal stability. Glass-reinforced grades are also available.

7-2.1 RAW MATERIAL PARAMETERS

Proper stabilization of compounds, as well as proper operating temperatures, is important when acetal resins are used to produce rotocast parts.

It is recommended that the acetal copolymer be ground 30-100 mesh ($<$ 5 percent by weight through 100 mesh) for rotocasting. This provides a particle size distribution that can be met readily by commercial grinding equipment.

A 20 percent glass-fiber-reinforced grade of the acetal copolymer has been successfully used commercially in a rotocast military application. The glass particle size, even

though reduced by grinding, imparts the required stiffness and high-temperature creep resistance needed. Other properties improved by glass addition are dimensional stability, lower coefficient of thermal expansion, and higher deflection temperatures.

The higher the melt index of the resin used, the better the material flows during the last portion of the heating cycle, producing a smooth inner surface.

Suppliers are

1. Celanese Plastics Co.
   550 Broad Street,
   Newark, N.J. 07102
   Celcon M-90

2. E.I. du Pont de Nemours & Co., Inc.
   Wilmington, Del. 19898
   Delrin 500

Costs are approximately $0.95 per lb.

7-2.2 PROCESS PARAMETERS

7-2.2.1 Drying Cycle

Fig. 7-1 shows the effect of relative humidity on moisture absorption of ground resin. These tests were conducted by exposing approximately 1/8 in. depths of resin to constant humidity conditions and determining the weight gain with time. At 50 percent relative humidity the ground resin absorbed only 0.09 percent moisture. At 100 percent relative humidity, moisture absorption was fairly rapid. It has been found that moisture levels of a few tenths of a percent can be excessive. Therefore, care should be taken to minimize exposure of the ground resin to high humidity conditions.

If the ground resin contains excessive moisture, then the surface of the rotocast parts will be marred by small bubbles or blisters. The parts also will be somewhat porous, resulting in a lower part density and tensile strength. For best results, resin should
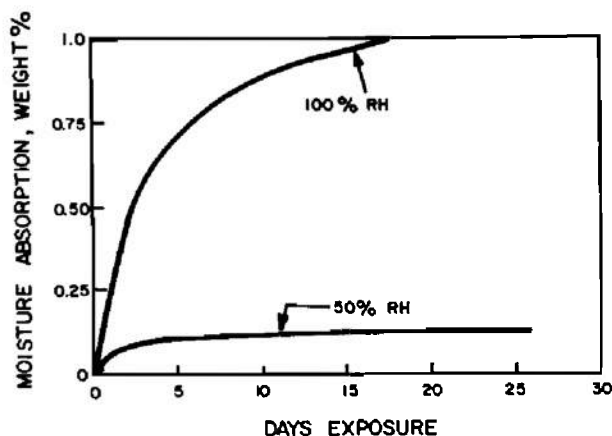
Figure 7-1. Effect of Relative Humidity on the Moisture
Absorption of Ground Celcon M-90[1]

be rotocast soon after grinding. If the material is stored, it should be in moisture-proof containers or foil-lined bags. Poor surface appearance of parts may be corrected by drying resin at 200°-225°F. Usually, drying times of one to two hours in a circulated-air oven are sufficient[1].

7-2.2.2 Heating Cycle

Normal oven temperatures in a recirculated hot-air heating system are 400°-500°F. When producing thick-walled parts (> 0.25 in.) normal production operating temperatures are 420°-450°F. For thinner-walled parts higher oven temperatures can be used to reduce the heating time. A problem could arise in rotocasting thick-walled parts at higher oven temperatures (~ 500°F); it is possible for the outside wall to start degrading before the complete part is fused.

For comparison, a curve for a 0.96 density grade of polyethylene is shown in Fig. 7-2. This curve was generated at an oven temperature of 500°F. Curves of the type in Fig. 7-2 can be used only to obtain the approximate heating conditions for production machines. Variations in mold thickness, mold surface area/resin charge, and air circulation rates can alter the heating conditions for the wall thickness desired.

7-2.2.3 Rotation

Normal rotational speeds and ratios are used in rotocasting the acetal copolymer. For every part geometry the optimum speeds and ratio should be determined by trial runs to obtain the degree of wall thickness uniformity desired.

7-2.2.4 Cooling Cycles

Rapid cooling, however, with a crystalline polymer such as acetal copolymer promotes part warpage and locked or "frozen-in" stresses in the finished part. These problems can more than offset any advantage in shrinkage or reduced cooling time gained from rapid cooling. Molds should be designed using proper shrinkage values for the material being rotocast; therefore, warpage is usually the controlling factor in producing rotocast parts. To minimize warpage, parts are cooled while rotating in air with a light water spray or mist applied for the last few minutes of the cooling cycle[1].

7-2.3 MOLD RELEASE AGENTS

Normally, no mold release is needed when rotocasting acetal copolymers. The shrinkage is usually sufficient to allow parts to be easily removed from the molds. If a mold release is
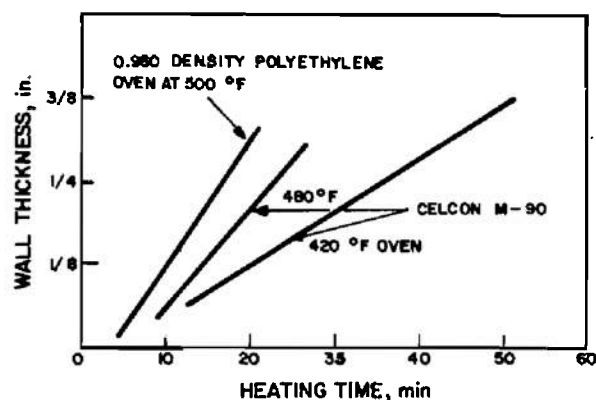
Figure 7-2. Effect of Heating Time on Part Wall Thickness of Plaster
Cast Aluminum (Mold cavity 9 X 11 X 6 in. Depth[1].)

needed, both baked-on silicone and Teflon®
coatings have been used successfully. Spray
type mold releases must be used sparingly. If
too much mold release is used, parts will tend
to draw away from the mold wall during the
cooling cycle and result in part warpage. A
light coating of fluorocarbon spray in corners
or ribbed sections of the mold should be
sufficient for producing numerous parts[1].

7-2.4 PROPERTIES

Typical properties of rotocast Celcon M-90
are shown in Table 7-1; properties of
Delrin 500, in Table 7-2.

TABLE 7-1

TYPICAL PROPERTIES OF ROTOCAST
CELCON M-90[1]

Tensile strength, psi	8200 - 8800
Tensile modulus, psi X 10^{-5}	3.9 - 4.2
Izod impact strength, ft-lb/in. of notch	1.0 - 1.2
Density, g/cm³	1.37- 1.38
Melt index, g/10 min	9.0
Shrinkage, %	2 - 0
Powder mesh size	30 - 100
	(<5 % by weight through 100)

To demonstrate the excellent creep re-
sistance of the glass-reinforced acetal copoly-
mers for use in a pressurized container,
flexural creep tests were conducted at 165°F
and 95 percent relative humidity[1]. These test
conditions are similar to the highest tempera-
ture-humidity requirements of military en-
vironmental testing. Fig. 7-3 shows the
superiority of the acetal copolymer over a 40
percent glass-reinforced grade of nylon 6/6.
Samples for testing were obtained from
rotocast containers.

7-3 ACRYLONITRILE BUTADIENE STY-
RENE (ABS)

The rotational molding of ABS is still
experimental. The present materials have
yielded hard but brittle products. Tougher
material development is required by the resin
suppliers. Therefore, little information is
available.

7-3.1 RAW MATERIAL PARAMETERS

Particle sizes of 30-35 mesh are
recommended.

There are no U.S. suppliers. The only
supplier is Daicel ABSROM® which is

TABLE 7-2

PROPERTIES OF DELRIN 500[2]

Impact strength, izod ft-lb/in.	$-40°F$	1.2
	$73°F$	1.4
Tensile strength, psi	$-68°F$	14,700
	$73°F$	10,000
	$158°F$	7,500
Flexural yield strength, psi		14,100
Flexural modulus, psi	$73°F$	410,000
	$170°F$	190,000
	$250°F$	90,000
Compressive stress, psi	1% deformation	5,200
	10% deformation	18,000
Deformation under load, %	2000 psi at $122°F$	0.5
Melting point (crystalline), $°F$		347
Flow temperature, $°F$		363
Specific heat, Btu/lb-$°F$		0.35
Thermal conductivity, Btu/hr-ft^2-($°F$/in.)		1.6
Coefficient of linear thermal expansion, per $°F$		4.5×10^{-5}
Flammability, in./min		1.1
Water absorption, %	24 hr immersion	0.25
	equilibrium, 50% RH, $77°F$	0.2
	equilibrium immersion $77°F$	0.9
Rockwell hardness		M 94, R 120
Specific gravity		1.425
Poisson's ratio		0.35
Heat of combustion, Btu/lb		7,400
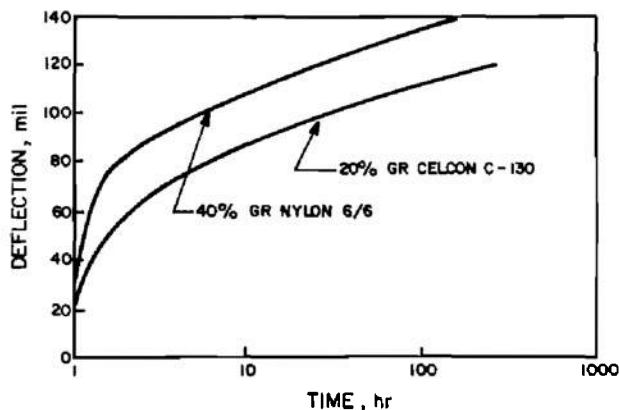
Reprinted by permission of SPE.

Figure 7-3. Flexural Creep of Rotocast Glass-reinforced Materials[1]
(165°F — 95% RH, 1500 psi Fiber Stress)

Japanese. The approximate price is $0.72 per lb.

7-3.2 PROCESS PARAMETERS

Oven temperatures between 550° to 800°F have been employed, depending on facilities used. Cycle times have ranged from 4 to 8 min depending on the cooling system. Water cooling is preferred but air cooling has also been employed[3].

7-4 CELLULOSICS

The cellulosic plastics generally used for rotational molding are cellulose butyrate and cellulose propionate. They are tough materials and normally used in applications utilizing their clear-transparent or translucent optical properties such as signs and lighting fixtures.

7-4.1 RAW MATERIAL PARAMETERS

Cellulose butyrate and cellulose propionate are offered for rotational molding in 1/16 in. (1.6 mm) pellets and in 18 mesh (0.82 mm) powder. Pellets are available in almost any color; 18 mesh powder, in clear-transparent and translucent white[4].

Some applications have been most successful with powder, some with pellets, and some

with a mixture of the two. Pellets exhibit more uniform melting and flow-out, and have less tendency than powder to bridge across corners and restricted areas. Powder melts more quickly than pellets and tends to fill small surface details better in some instances.

TENITE® cellulosics can be mixed with higher-melting materials to produce unusual effects. Some of the materials that have been used are pellets of harder-flow (higher-melting) TENITE® cellulosic formulations, rigid-vinyl chips, metallic flake, and polystyrene pellets. These materials flow little or not at all during the molding operation, and they therefore remain as discrete particles within the wall or on the interior surface of the finished piece. A decorative light globe made of transparent or translucent TENITE® cellulosic mixed with some of these other materials and internally illuminated can give striking appearances.

The resin supplier for TENITE® Butyrate 457 and TENITE® Propionate 335 is Eastman Chemical Products, Inc. Both of these formulas contain very high-boiling plasticizers—an important factor at the temperatures generally used for rotational molding. The flow generally suggested is MS, S, or S2*

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*These designators refer to varying degrees of softness from MH down to S2.

for TENITE® Butyrate 457; MH, M, or MS for TENITE® Propionate 335. Costs are approximately $0.90 per lb.

7-4.2 PROCESS VARIABLES

7-4.2.1 Drying Cycle

Cellulosic plastics absorb small amounts of water from the atmosphere and should be dried before they are molded. Drying for 2 hrs in a dehumidified-air oven at 130°-150°F (54°-66°C) generally is recommended.

When undried or inadequately dried, the absorbed moisture turns to steam as the plastic heats. If the mold is vented, most of the steam will escape through the vent; but some may be trapped within the heat-softened plastic and cause bubbles in the finished product. However, bubbles in the molded item do not necessarily mean that the plastic needs additional drying.

7-4.2.2 Heating Cycle

The oven temperature for rotationally molding TENITE® should not exceed 500°F (260°C). Higher temperatures can cause excessive degradation and the release of volatile materials inside the mold, as well as excessive vaporization of the plasticizers. If organic vapors concentrate inside the mold at temperatures above about 500°F, they can form combustible mixtures with the oxygen that will enter through the mold vent when cooling is begun. If autoignition or ignition by a static spark should occur under these conditions, the resulting flash fire inside the molded article would result in a sudden large increase in pressure in the mold. This sequence of events can lead to mold rupture, and even to explosion of the mold with potentially dangerous force. The possibility of such accidents can be minimized by use of rotational molding formulas (not a formula with a lower-boiling plasticizer), by continuous purging of the mold with inert gas,

and by proper control of the temperature. No flash fires of the type described have been reported at oven temperatures below 500°F (Ref. 4).

The time required for melting the plastic inside the mold will vary with the size of the mold and the size of the charge. A light globe having a wall thickness of approximately 1/8 in. (3 mm), weighing about 1.1 lb (500 g) required heating about 11 min at 500°F (Ref. 4).

7-4.2.3 Rotation Rates

Experience has shown that the most nearly uniform wall thickness has resulted when the major-axis-to-minor-axis rotation ratio is about 4 to 1. Also, the most nearly uniform wall thickness has resulted when the rotation was as slow as possible down to 6 rpm for the major axis. If the mold is of a particularly odd shape, however, another ratio or a higher rotation rate might be better[4].

If the plastic remains in the oven too long, it will begin to degrade. A change in color is evidence that it has undergone slight overheating, and a badly discolored or brittle item indicates that extreme overheating has occurred.

Wall roughness indicates that the plastic has not been heated enough to cause it to flow into a smooth layer. Heating time can be increased to promote better flow-out of the plastic; or the oven temperature can be raised as long as the safe limit is not exceeded.

Bubbles in a molded item are formed by gases (air or vapor) that are trapped within the plastic when it melts. If thorough drying of the plastic fails to eliminate the bubbles, a slight reduction in oven temperature, with consequent slower melting of the plastic, is recommended. There is no technique currently known, however, that will ensure bubble-free rotationally molded pieces.

7-4.2.4 Cooling Cycle

Generally, cellulosics are cooled first in a water-spray. Like the heating time, the required cooling time varies with the size and weight of the article. A 1/8 in. thick light globe required about 5 min of water spray[4]. When spraying is discontinued, the still-warm mold is dried by forced air. The mold then can be opened and the molded items are ready for removal. Adequate cooling is necessary if the molded article is to be removed easily from the mold. The mold is cooled sufficiently when it is no longer uncomfortably hot to the touch.

Water entering the vent or the junction of the mold sections may spot transparent plastic or cause bubbles to form in the wall of the molded piece. If this becomes a problem, the water spray can be omitted and the mold cooled with forced air.

7-4.3 MOLD RELEASE AGENTS

Before a mold is charged with plastic, its inside surfaces must be clean. If initial trials show that the molded item is difficult to remove from the mold, the mold may be treated with a mold-release agent. These are generally silicone compounds, and two types are available—sprays that must be used every few moldings, and longer-lasting, baked-on finishes that will be effective for several days of normal operation. Some mold-release agents used specifically for rotational molding are obtainable from Fre-Kote, Inc., 2300 N. Emerson Avenue, Indianapolis, Ind. 46218; Orb Industries, Inc., P. O. Box 544T, Media, Pa. 19063; Specialty Products, Inc., 15 Exchange Place, Jersey City, N.J. 07302; and Stauffer Chemical, 299 Park Avenue, New York, N.Y. 10107.

7-4.4 PROCESS EQUIPMENT

Cast aluminum molds frequently are used,

but molds with hard, nonporous surfaces frequently will give parts with better appearance. There is a tendency for pores in cast aluminum to trap air, which will expand after the plastic melts and seals over it; the result is air bubbles in the surface of the molded article. These bubbles are particularly noticeable when the plastic is transparent.

Molds should be vented. Flexible polyfluorocarbon tubing is excellent for this purpose. A vent area of 0.25 in.^{2} for each cubic foot of mold volume (ca. 6 mm^2 per liter of mold volume) is usually adequate[4].

7-4.5 PROPERTIES

Some of the properties of cellulosics are given in Table 7-3.

7-5 FLUOROCARBONS

Ethylene-chlorotrifluoroethylene (E-CTFE) is a copolymer of ethylene and monochlorotrifluorethylene in a special powder form. "Halar"® resin 5002 combines the high-performance properties of fluoropolymers with the processing ease of rotomolding. This fluoropolymer is highly resistant to chemical attack and stress cracking in organic, mineral, and oxidizing acids, bases, salts, and peroxides. It has low permeability, and there is no known organic solvent for it up to 250°F.

7-5.1 RAW MATERIAL PARAMETERS

Halar® 5002 is supplied as a free-flowing powder having a bulk density of 40 lb/ft^3. Resin requirements may be calculated on the basis of 0.009 lb of Halar® E-CTFE per square foot of surface area per 0.001 in. of wall thickness.

The supplier is Allied Chemical Corp., P.O. Box 2365R, Morristown, N.J. 07960. Approximate cost per pound is:

TABLE 7-3
PROPERTIES OF TENITE® CELLULOSIC PLASTICS
FOR ROTATIONAL MOLDING[4]

PROPERTY, UNIT [SPECIAL CONDITIONS OF TEST]	ASTM TEST METHOD	TENITE BUTYRATE 457			TENITE PROPIONATE 335		
		MS	S	S2	MH	M	MS
Flow Temperature, °F	D 569	284	275	266	302	293	284
Specific Gravity	D 792	1.18	1.17	1.16	1.19	1.18	1.18
Hardness, Rockwell, R Scale	D 785	61	—	—	—	—	—
Tensile Strength at Yield, psi	D 638	3,100	2,600	2,150	3,000	2,350	1,700
Tensile Strength at Fracture, psi at 73°F (23°C)	D 638	4,400	3,900	3,450	3,600	2,900	2,200
at 158°F(70°C)		2,150	1,850	1,550	2,000	1,650	1,250
Flexural Strength at Yield, psi	D 790	4,450	3,700	3,000	4,200	3,400	2,600
Stiffness in Flexure, 10^5 psi	D 747	1.05	0.90	0.80	1.15	0.95	0.85
Impact Strength, Izod, ft-lb/in. of notch at 73°F (23°C)	D 256	6.9	7.8	8.8	7.5	8.0	No break
at −40°F (−40°C)	D 758	1.2	1.2	1.3	1.6	1.9	2.2
Deformation Under Load, % [24 hr at 122°F (50°C)] at 1000 psi	D 621	8	16	27	5	10	15
at 2000 psi		28	39	46	26	37	>40

INJECTION-MOLDED SPECIMENS 1/8 IN. THICK

TABLE 7-3 (Cont'd)

PROPERTIES OF TENITE® CELLULOSIC PLASTICS FOR ROTATIONAL MOLDING[4]

PROPERTY, UNIT [SPECIAL CONDITIONS OF TEST]	ASTM TEST METHOD	TENITE BUTYRATE 457			TENITE PROPIONATE 335		
		MS	S	S2	MH	M	MS
Water Absorption, % [24-hr immersion]	D 570	1.1	1.0	0.9	1.7	1.6	1.5
Soluble Matter Lost, %		-0.1	0.1	0.1	0.1	0.1	0.1
Weight Loss on Heating, % [72 hr at 180°F (82°C)]	See Note	0.3	0.4	0.5	0.5	0.6	0.7
Hardness, Rockwell, R Scale	D 785	74	—	—	—	—	—
Impact Strength, Izod, ft-lb/in. of notch at 73°F (23°C)	D 256	3.3	4.0	4.7	4.8	6.0	6.5
at −40°F (−40°C)	D 758	0.8	0.9	0.9	1.1	1.2	1.3
Compressive Strength at yield, psi	D 695	4,500	3,700	3,100	2,700	1,950	1,250
Deflection Temperature, °F at 264-psi fiber stress	D 648	138	131	126	128	121	118
at 66-psi fiber stress		157	149	142	154	144	134

INJECTION-MOLDED SPECIMENS 1/8 IN. THICK

COMPRESSION-MOLDED SPECIMENS 1/2 IN. THICK

Note: D707 for TENITE Butyrate; D1562 for TENITE Propionate
All tests run at 73°F (23°C) and 50 percent RH unless otherwise specified.

Type	10-99 lb	100-1,999 lb	2,000 lb & Over
5001 (Rotomolding, coarse)	$7.40	$7.20	$7.00
5002 (Rotomolding, fine)	$7.65	$7.45	$7.25

7-5.2 PROCESS VARIABLES

7-5.2.1 Drying Cycle

Halar® E-CTFE is not hygroscopic and need not be dried prior to rotomolding.

7-5.2.2 Heating Cycle

Oven temperatures ranging between 540° and 675°F have been successfully employed in rotomolding Halar® E-CTFE. Temperatures in the 550°-600°F range are recommended because temperatures above 610°F tend to cause small surface bubbles.

Cycle time must be determined experimentally for each part. To determine optimum cycle, it is recommended that cycle times be approached from the short side and increased until complete flow-out is achieved. Specific gravity and tensile property measurements are excellent quality control checks to confirm the integrity of moldings. Some examples of typical Halar® polymer heating cycles are shown in Table 7-4[5].

Table 7-5 lists conditions that have been used to rotoline valves and fittings with E-CTFE resin. Similar conditions can be used effectively as starting conditions for establishing other cycle conditions. Cycles times are slightly longer when using PTFE end caps, inasmuch as PTFE is a thermal insulator. Rotolining is a technique for lining hollow metal objects with thermoplastic resins. It is essentially identical with rotomolding except: (1) the object acts as the mold, and (2) the thermoplastic is not removed from the "mold", but remains an integral coating within the metal part. Parts that lend themselves to rotolining include tanks, ductwork, pipe, valves, T's, Y's, crosses, and reducers.

7-5.2.3 Cooling Cycle

Halar® resin crystallizes at a rapid rate and to a high degree of crystallinity on cooling. For this reason, Halar® may be cooled rapidly with water after only a brief 1-2 min air fan cool without exhibiting marked distortion[5]. Cooling cycles of 1 to 2 min fan cool, 4 to 8 min water spray, and 1 to 3 min fan dry are satisfactory for cooling 2- to 4-in. cast-

TABLE 7-4

EXAMPLES OF TYPICAL HALAR® HEATING CYCLES

PART	MOLD	WALL THICKNESS, in.	TEMP, °F	OVEN TIME, min
Hair dryer case	1/4 in. aluminum	0.075	600	13
18 in. X 4 in. X 6 in. tank	1/16 in. sheet metal	1/16	565	14
6 in. spherical globes	1/4 in. cast aluminum	1/8	565	14
2 in. pipe T	1/2 in. cast ductile iron	0.140	600	25

TABLE 7-5

SUGGESTED ROTOLINING STARTING CONDITIONS[a6]

PART	END CAP MATERIALS	SHOT WEIGHT (1/8-in. LINER), g	TIME, min[b]	OVEN TEMP, °F	ROTATION RATIO
2-in. pipe'T'	Al or steel	19-20	24-30	600-620	4:1 or 8:1
	TFE	13-14	27-33	600-620	4:1 or 8:1
2-in. 90 deg	Al or steel	12-14	23-28	600-620	8:1[c]
long-radius 'L'	TFE	8-9	26-30	600-620	8:1[c]
	TFE	8-9	24-25	640	8:1[c]
1½-2 in. diaphragm valve	Al or steel	8/12-13	25-29	600-620	4:1 or 8:1
4-in. pipe 'T'	TFE	5/9-10	29-33	600-620	4:1 or 8:1
	TFE	40-48	44-48	620	4:1 or 8:1
	TFE	40-48	35-40	675	4:1 or 8:1
4-in. 90 deg long-radius 'L'	TFE	24-26	44-48	620	620 8:1[c]

a. Suggested on the basis of experimental data with McNail Corp. rotomolding machines. In theory, shorter cycles can be obtained by heating precharged castings at 700° to 800°F to raise casting temperature rapidly to 450° to 500°F then reducing oven temperature to about 550°F to effect fusion and flowout.
b. Time will vary with machine due to differences in temperature calibration and heating response rate.
c. Mounted horizontally.
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ings. There has been no evidence of property variation during such cooling cycles[6].

7-5.3 MOLD RELEASE AGENTS

Bake-on silicone or fluorocarbon mold release agents can be used if part sticking is a problem. However, mold release must be used sparingly as excessive mold release tends to cause premature release from the wall during cooling, resulting in part warpage[5].

7-5.4 PROCESS EQUIPMENT

Conventional rotational molds such as plaster-cast aluminum types are used with Halar® 5002, but generously radiused corners in excess of 0.5 in. are recommended to produce smooth surfaces of uniform thickness.

All surfaces in contact with hot E-CTFE must be made of corrosion resistant materials such as "Xaloy" 306, B.C.I. N02, Duranickel, Hastelloy C, 303 or 416 stainless steels, or steel which has been hard chrome plated and the plating tested and found to be free of pinholes. It is especially important to prevent contact of the melt with copper alloys and unprotected tool steel as such contact will reduce the melt stability of the resin. Venting of molds is recommended.

End caps are used to seal the ends of rotolined castings. Caps made from spun steel, machined steel, aluminum, and 1 in. thick PTFE have been employed successfully. To permit resin to flow onto flange faces, end caps must have a raised or machined-out section approximately 5/8 in. deep, with a diameter 1/8 in. less than the interior of bolt-hole-circle diameter.

The PTFE end caps have the additional advantage of reducing resin requirements and minimizing post finishing operations, since resin will not adhere to PTFE. A 1/4-in. aluminum plate on top of the cap minimizes warpage and prolongs its useful life. Metal end caps should be coated

with a bake-on mold release to enable removal of the cap.

One end cap should be vented to reduce pressure buildup during heating, and to permit the entry of air upon cooling[6].

7-5.5 PROPERTIES

Typical properties of Halar® 5002 are shown in Table 7-6.

7-6 IONOMER

The ionomer resins possess superior impact strength, especially at sub-zero temperatures. Abrasion resistance and absence of plasticizer make ionomers unique thermoplastic materials for rotational molding process.

7-6.1 RAW MATERIAL PARAMETERS

Surlyn® A1558 is a rotational molding ionomer. This resin offers superior impact strength retention at low temperatures, easy processability, and is easy to grind.

A 35-mesh grind has proven to be too fine for ionomers. The most successful parts have been made with a nominal mesh grind that has a peak particle size distribution of from 25 to 40 mesh. Particle shape is as important as the correct particle size for the production of quality parts. The optimum shape, i.e., regular spheres or cubes with no tails, is only attainable when the grinding process is carefully monitored and controlled.

Melt blending in an extruder gives the best dispersion of pigments or filler materials. Certain pigments such as carbon black and titanium dioxide (white) are very hard to disperse by dry blending. Low pigment loadings (less than 0.1 percent by weight) of color pigments can be made successfully. Higher pigment loadings (more than 0.25 percent by weight) can coat the resin particles and result in poor particle fusion and consequent loss of impact strength.

Ionomers lend themselves to in-place foaming. This foaming is accomplished by dry blending a small amount (one to two percent by weight) of a dry foaming agent with the ionomer powder before placing it in the mold. Sodium bicarbonate and 'Celogen'* AZ seem to be the most successful blowing agents that have been tested. With one to two percent by

*Uniroyal Corp. costs are approximately $0.50 per lb.

TABLE 7-6

TYPICAL PROPERTIES OF HALAR® 5002 ROTOMOLDINGS[5]

PROPERTY	UNITS	TEST METHOD	VALUES
PHYSICAL			
Bulk Density	lb/ft³	ASTM D 1895	40
Specific Gravity	—	ASTM D 792	1.69
Melting Point	°F	DSC	465
DTUL at 264 psi stress	°F	ASTM D 648	170
Brittleness Temperature	°F	ASTM D 746	< -110
Thermal Expansion	°F^{-1}	ASTM D 696	14×10^{-5}
Thermal Conductivity	Btu/hr-ft²-(°F/ft)	—	1.1
Radiation Resistance	rad	—	Retains Useful Properties to 10^9 rad
Mold Shrinkage	in./in.-°F	—	0.01

TABLE 7-6 (Continued)

TYPICAL PROPERTIES OF HALAR® 5002 ROTOMOLDINGS[5]

PROPERTY	UNITS	TEST METHOD	VALUES
MECHANICAL			
Tensile Strength at	psi	ASTM D 1708	
Yield			4200
Break			6000
Elongation at	%	ASTM D 1708	
Yield			5
Break			200
Flex Modulus	psi	ASTM D 790	240,000
Tensile Creep Modulus	psi	ASTM D 674	90,000
at 1500 psi stress,			
250 hr			
Notched Izod Impact			
Strength	ft-lb/in^{-1}	ASTM D 256	
at 73°F			No Break
at −40°F			2-3
Drop Weight Impact	ft-lb	Tup A of	
Strength		ASTM D 2444	
at 73°F		4 in. dia, 90 mil thick	> 140
at −85°F		sheet on 3 in. ID support	65
Hardness	Rockwell R	ASTM D 785	93
Armstrong Abrasion	Vol loss, cm^3	ASTM D 1242	0.3
		Method B	
FLAMMABILITY			
Limiting Oxygen Index	% O$_2$	ASTM D 2863	60
U.L. Vertical, 0.01 in.	—	Bulletin 94	Meets SE-0
Federal Standard			
ccc-T-19 lb-5903			
Flame-out time	sec		0
Burn length	in.		2.7
ELECTRICAL			
Dielectric Constant/		ASTM D 150	
Dissipation Factor			
at 60 Hz	—		2.6/0.0009
at 1 kHz	—		2.6/0.003
at 1 MHz	—		2.5/0.01
Dielectric Strength	V/mil	ASTM D 149	
Short Time			
0.125 in.			490
0.040 in.			1000
0.010 in.			2000
Volume Resistivity	ohm-cm	ASTM D 257	> 10^{15}

weight of these blowing agents added to the resin in the mold, part densities of 15 to 20 lb/ft³ are attainable. At the end of the cycle, foamed parts with excellent rigidity and high impact strength are extracted from the mold.

The resin supplier is E. I. du Pont de Nemours & Co., Inc., Wilmington, Del. Surlyn® A1558 is approximately $0.49 per lb.

7-6.2 PROCESS VARIABLES

7-6.2.1 Drying Cycle

Ionomers are hygroscopic. Grinding these resins greatly increases the surface area available for moisture pick-up. Therefore, ground hydroscopic resins will pick up moisture more rapidly than the same resins in normal pellet form. Additives, such as carbon black, can also increase the rate at which moisture is picked up. The moisture can vaporize during molding and create bubbles and pitting of the part surface. If possible, the resin should be stored in a low humidity environment and containers of resin should be kept closed. Overnight drying in a dehumidified oven at 50°C will eliminate most of the moisture.

7-6.2.2 Heating Cycle

The oven cycle time and temperature are similar to the oven cycle used for HDPE. Using these settings as a starting point, the cycle can be established accurately with a few trial moldings. Oven residence time should be kept to a minimum after a smooth inner wall of the molded part is attained. A yellow or light brown tint in the corners or along the parting line indicates excessive oven time and/or temperature. Oven air temperature should be around 700°-850°F (370°-455°C) to minimize induction time. The optimum oven cycle for foaming is longer and cooler than a regular part. A 120-mil wall requires 10 min at 700°F (371°C); a foamed part using the same weight of resin requires about 15

min at 525°F (274°C) (Ref. 7).

7-6.2.3 Cooling Cycle

Ionomers are less sensitive to cooling rate changes than HDPE and can be cooled more slowly without losing toughness. This slower cooling can be obtained with a medium water spray. The advantage of this cooling rate is reduced part warpage. Slow cooling with air is unnecessary.

7-6.3 MOLD RELEASE AGENTS

Severe part sticking in the mold occurs when fluorocarbon spray mold release agents are used. A wipe on-wipe off silicone oil is recommended. It usually is applied before each shot.

7-6.4 PROCESS EQUIPMENT

The molds suggested for rotational molding ionomers are the standard cast aluminum, spun aluminum, electro-formed nickel plated, and fabricated sheet steel used for HDPE. Since surface detail of the mold is duplicated accurately on the outer surface of the ionomer part, a polished mold is required to produce a very smooth part. The most important factor in reducing the bubble count in an ionomer molding is the surface finish of the mold. The use of a polished nickel mold greatly reduced the number of bubbles when compared to moldings made in a cast aluminum mold. Small pores in the aluminum surface apparently trap air that in turn forms bubbles in the part which are nearly impossible to drive out. The nickel surface is so smooth that very little air is trapped which accounts for the relatively few bubbles in the part. The mold should be vented. This venting will prevent the part from collapsing as the hot air trapped inside contracts upon cooling[7].

7-6.5 PROPERTIES

Typical properties are listed in Table 7-7.

TABLE 7-7

TYPICAL IONOMER PROPERTIES

PROPERTIES	ASTM TEST METHOD	TEST DATA
Melt index, g/10 min	D 1238	5.0
Mold shrinkage, in./in.	D 955	
Specific gravity	D 972	0.935
Water absorption, %	D 570	
Tensile strength, kpsi	D 638	2.4
Flex modulus, kpsi		32.0
Tensile impact, ft-lb/in.^{2}		
at 73°F		141
at 0°F		56

7-7 NYLONS

In comparison with other thermoplastics, the nylons offer superior strength, toughness, low temperature resistance, solvent resistance, and low permeability of hydrocarbons. To date, three nylons—nylon 6, 11, and 12—are rotomolded commercially.

7-7.1 NYLON 6

Nylon 6 is more moisture sensitive and more subject to yellowing than nylons 11 and 12. Nylon 6 also may require an inert gas atmosphere during processing to avoid embrittlement. Parts when removed from molds are normally bone dry and very brittle.

7-7.1.1 Raw Material Parameters

A 35-mesh particle size is recommended. Costs are approximately $1.00 per lb.

7-7.1.2 Process Variables

Predrying nylon 6 is not required. Oven temperatures in the 500°-600°F range have been successful, depending on part and mold variables. Oven cycle times of approximately 30 min have been reported. Cooling has been accomplished by combination of air followed by 5-min water spray. Release agents are required[8]. Presently there are no nylon 6 powder suppliers.

7-7.2 NYLON 11

To date nylon 11 has the widest acceptance of the commercial grades of nylon for rotational molding. This is due to its lower gravity 1.04, 40°F lower cold impact, low moisture sensitivity, improved chemical resistance, and lower melting point facilitating ease and speed of processing.

7-7.2.1 Raw Material Parameters

Rilsan GSMR nylon 11 is supplied as a ground powder and is available only in natural color. However, it is possible for the molder to introduce suitable colorants, and items rotationally molded from Rilsan GSMR can be dyed.

The particle size of GSMR has been tailored to give rapid, uniform melting of the particles. The particle size distribution includes:

1. 10% of particles larger than 300 μ

2. 10% of particles smaller than 100 μ.

These values can be taken only as an approximate guide since the particles tend to be irregular rather than spherical in shape.

One of the specific properties of GSMR, and of Rilsan, is its low moisture regain. This is particularly important in the volume-surface relation of the particles. The low moisture regain stops the formation of steam bubbles that might appear during processing.

Nylons are known for their susceptibility to oxidation. GSMR has been modified by the inclusion of an additive that protects it against oxidative degradation during the molding cycle. Therefore, it is not necessary to use an inert gas (nitrogen), which involves more costly and complex equipment. The supplier is the Rilsan Corporation, 139 Harristown Road, Glen Rock, New Jersey

TABLE 7-8

SHRINKAGE ASSOCIATED WITH HEATING OF GSMR

WEIGHT OF GSMR, g	AVERAGE THICKNESS, mm	HEATING TIME AT 280°C	SHRINKAGE, %	
			DIAMETER	HEIGHT
120	1.9	7' 30"	2.7	1.8
135	2.1	7' 40"	2.8	2
150	2.4	8'	2.9	2.1
200	3	9' 30"	2.9	2.15

07452. Costs of nylon 11 are approximately $1.60 per lb.

7-7.2.2 Process Variables

7-7.2.2.1 Drying Cycle

None.

7-7.2.2.2 Heating Cycle

Oven temperatures for GSMR range between 536°F (280°C) and 572°F (300°C) for an acceptable item. The duration of heating is a function of the temperature selected, the thickness of the plastic wall, and the mold, and is finally determined during the preliminary tests. The chosen time will be slightly higher than that necessary to make the last fragments of GSMR powder adhere to the already melted product (usually 2 to 10 min).

The heating time, as a function of the weight of powder introduced into the mold, and the shrinkage of the pieces 24 hr after molding, are shown in Table 7-8[10].

Figs. 7-4 and 7-5 plot the heating time versus wall thickness and oven temperature.

7-7.2.2.3 Cooling Cycle

Cooling is effected by water spray (approximately 3 min) on the mold during rotation until the material solidifies.

7-7.2.3 Mold Release Agents

In order to extract the molding from the mold more readily it is advisable to spray the inside of the mold with a thermosetting resin; examples are:

1. A2 resin, marketed by Etablissements ROBERT, 6, rue de Verneuil, Paris (7e);

2. 4673 resin, made by RHONE-POULENC.

3. DP 290 resin obtainable from I.C.I. polymerizes at ambient temperature.

Resins A2 and 4673 must be baked at 140°C for about 30 min.

The inside of the mold must be polished and free from porosity. Silicone-based release agents also can be sprayed on the walls of the mold to assist mold release.
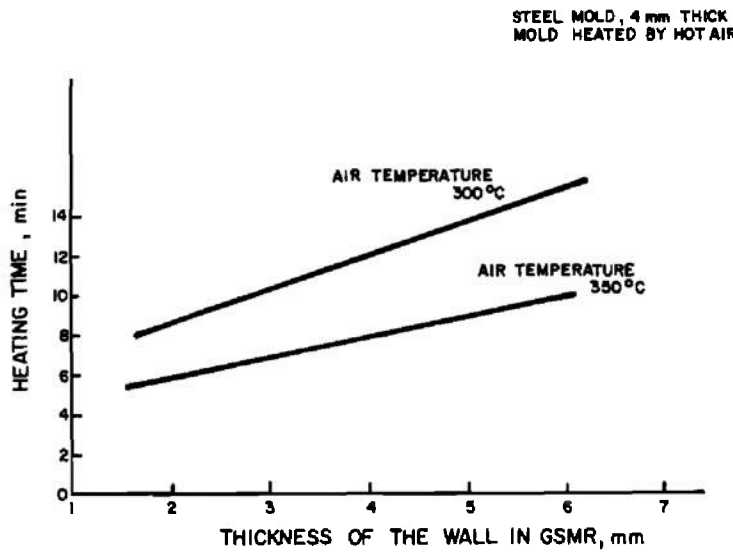
Figure 7-4. Heating Time as a Function of Required Thickness of GSMR[10]
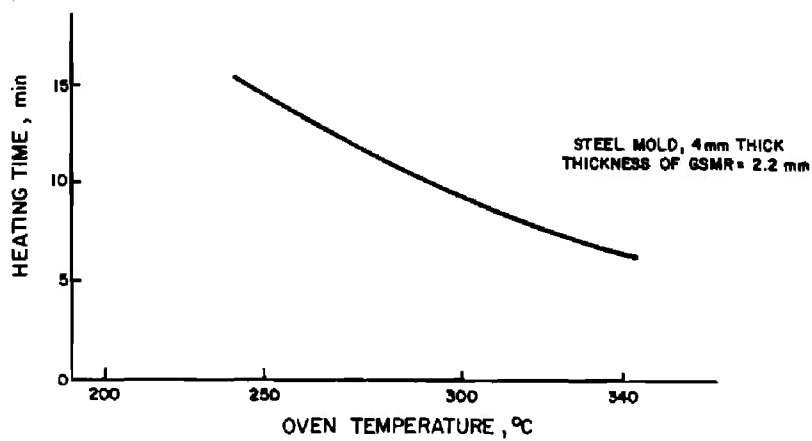
Figure 7-5. Heating Time as a Function of Oven Temperature [10]

7-7.2.4 Properties

Table 7-9 presents the typical properties of Rilsan GSMR.

Rilsan GSMR has the same advantages as other nylons with regard to chemical inertness. Rilsan GSMR has good resistance to bases and saline solutions, to sea water and coastal atmospheric conditions, and to oils, greases, and petroleum products. Its resistance to mineral and organic acids varies in each case, so it is advisable to carry out tests under practical working conditions when possible.

The degree of shrinkage is a function of the geometric shape of the piece (strengthening ribs) and of the cooling time. An item will shrink 3 percent or more if it is cooled in the air or if the high calorific capacity of the mold leads to slow cooling.

7-7.3 NYLON 12

Nylon 12 combines the typical properties of nylon such as good mechanical and impact strength, high resistance to abrasion and to chemical and solvent attack, with properties similar to polyolefins. These properties include low water absorption (lowest water absorption of all commercial nylons), low density, and excellent low-temperature flexibility (no embrittlement to $-110°F$). They show a slow increase in the melt index with increasing temperature and, therefore, easy processing characteristics.

7-7.3.1 Raw Material Parameters

A supplier of nylon 12 is the Allied Chemical Company, P.O. Box 365, Morristown, N.J. 07960. The cost is approximately $1.60 per lb.

7-7.3.2 Processing Variables

7-7.3.2.1 Drying Cycle

None.

7-7.3.2.2 Heating Cycle

Heating temperatures of $550°-750°F$ are recommended if hot air convection ovens are used. Mold rotation speeds will vary according to the design and size of the article being molded. For small hollow objects without narrow projections, 10 to 12 rpm about the major axis and 2-3 rpm about the minor axis should be satisfactory[9].

Inert gas purging of the mold is not necessary for rotational molding of the specially heat-stabilized type 1640 powder, but should be used for unstabilized types to avoid any embrittlement that may occur on the inside surface of the object.

7-7.3.3 Mold Release Agents

Mold release agents, preferably of silicone or fluorocarbon type, must be used. Molds that previously have been used for molding vinyls may require special cleaning by sandblasting or hand scrubbing with pumice and water[9].

7-7.3.4 Equipment

Inexpensive split molds made of cast aluminum or electroformed copper-nickel are recommended for small or intermediate size articles; sheet steel, for large articles.

7-7.3.5 Properties

Table 7-10 presents the typical properties of nylon 12.

7-8 POLYBUTYLENE

This material is a flexible, crystalline, stereo regular polyolefin having a density of 0.91 and offering a unique combination of properties. Some of its important characteristics include: exceptional resistance to environmental and mechanical stress cracking, creep or cold flow, good toughness, high permissible working temperature (225°F

TABLE 7-9

TYPICAL RILSAN GSMRO PROPERTIES[10]

PROPERTY		UNITS	ASTM METHOD	GSMRO
Specific Gravity			D 792	1.04
Water Absorption	%	immersion 24 hr/73°F	D 570	0.3
		65% RH saturation/73°F	—	1.1
Tensile Strength	— 40°F			
	+ 68°F	kpsi	D 638	7.5
	+ 176°F			
Elongation	— 40°F			
	+ 68°F	%	D 638	150
	+ 176°F			
Impact Strength	— 40°F	ft-lb/in. of notch	D 256	
	+ 68°F			
Cold Brittleness Temp.		°F	D 746	−94
Taber Abrasion C17 wheel, 1000 q wt		mg/1000 cycles	D 1044	5
Hardness — Rockwell		R Scale/75°F/65% RH	D 785	108
Flexural Modulus	— 40°F			1.92
	+ 68°F	psi $\times$ 10^5	D 790	1.42
	+ 176°F			0.27
Compressive Strength		kpsi	D 695	10.0
Deflection	66 psi	°F	D 648	302
Temperature	264 psi			131
Melting Point Range		°F	D 2117	367-383
Linear Expansion Coefficient	— 22° + 104°F	$10^{-5}/°C$		15
	+ 104° + 248°F		D 696	15
Specific Heat		cal/g-°C	—	0.47
Thermal Conductivity		10^{-4} cal/sec-cm^2-(°C/cm)	—	8
Flammability		in./min	D 635	self-extinguishing
Volume Resistivity		ohm-cm 68°F/65% RH	D 257	7.8×10^{13}

TABLE 7-9 (Continued)

TYPICAL RILSAN GSMRO PROPERTIES[10]

PROPERTY		UNITS	ASTM METHOD	GSMRO
Dielectric Constant	100 cycles	—	D 150	3.9
	10^3			3.7
	10^6			3.1
Power Factor	100 cycles	—	D 150	0.044
	10^3			0.045
	10^4			0.042
Dielectric Strength — Short Time		V/mil (dry)	D 149	425
			Characteristics	For Rotational Molding Available in Colors

softening temperature), good stiffness, and low density. Polybutylene also provides excellent electrical insulation properties and resistance to most chemical environments.

7-8.1 RAW MATERIAL PARAMETERS

A particle size distribution in the range 25-200 mesh is recommended[11]. The supplier is Witco Chemical Corporation, Polymer Division, P.O. Box 305, Paramus, N.J. 07652. The cost for polybutylene rotomolding resins is approximately $0.43-0.45 per lb in truckload quantities.

7-8-2 PROCESSING VARIABLES

7-8.2.1 Heating Cycle

Oven temperatures in the range 500°-650°F with a 1/8 in. thick aluminum mold for part thickness 0.75-0.300 in. have given satisfactory results. Fig. 7-6 presents molding time versus part thickness at four oven temperatures.

Although venting is not required, the introduction of an inert gas is recommended

to retain the optimum properties when long cycle times and high temperatures are encountered.

7-8.2.2 Cooling Cycle

The cooling cycle consists of a 1-min delay in air followed by a 5-min water cooling period. Since part shrinkage is not a major problem with polybutylene, rapid cooling rates can be used and are desirable in order that the molded part possesses the maximum impact strength.

7-8.3 MOLD RELEASE AGENTS

Polybutylene does not exhibit any appreciable shrinkage immediately after molding. This necessitates the use of a mold release agent. Satisfactory results have been obtained using a wide variety of spray-on type release agents, e.g., a fluorocarbon type.

7-8.4 PROPERTIES

Polybutylene posses a unique characteristic in that it is relative soft and flexible immediately after molding. Hardness,

TABLE 7-10

TYPICAL PROPERTIES OF NYLON 12[9]

(A) PHYSICAL PROPERTIES

PROPERTY[3]	TEST METHOD	UNIT	STANDARD[1] TYPES
Density	ASTM D 792	g/cm^3	1.01-1.02
		lb/ft^3	62.9-63.5
Bulk Density	ASTM D 1895	g/cm^3	0.58-0.60
		lb/ft^3	36.2-37.5
Bulk Factor	ASTM D 1895	—	1.7-1.8
Melting Range	ASTM D 2117	°C	175-180
		°F	347-356
Water Absorption	ASTM D 570 Immersion in Water		
	at 23°C, 24 hours	%	0.25
	Long Term	%	1.4
Impact Strength	ASTM D 256		
	Method A	ft-lb/in.	2-5.5
Flexural Stress (at 5% strain)	ASTM D 790	psi	6800-7100
Flexural Modulus	ASTM D 790	psi	170,000-180,000
Tensile Stress at Yield	ASTM D 1708	psi	7000-7900
Elongation at Yield	ASTM D 1708	%	8-9
Tensile Strength at Break	ASTM D 1708	psi	6500-7400
Elongation at Break	ASTM D 1708	%	220-280
Rockwell Hardness	ASTM D 785[2]	—	R 106 M 31
Cold Impact	Drop Weight 200 g from 200 mm height. Test specimen at 0.5 mm	°F	Rupture at < −94
Dimensional Stability Under Heat (Vicat)	(ASTM D 1525) (Measured in oil)	°C °F	160-168 320-325
Thermal Conductivity	ASTM C 177	cal/sec-cm^2-(°C/cm)	5.3 × 10^{-4}
Coefficient of Linear Expansion	ASTM D 696	°C^{-1}	1.04 × 10^{-4}
Flammability	ASTM D 635	—	Self-extinguishing types 1600-1801; Burning types 1901-2101
Deflection Temperature	ASTM D 648	°C °F	49-55 120-131

(B) ELECTRICAL PROPERTIES

Insulation Resistance	ASTM D 257	ohm	2.5 × 10^{13}
Volume Resistivity	ASTM D 257	ohm-cm	2.5 × 10^{15}
Surface Resistivity	ASTM D 257	ohm	1.7 × 10^{15}

TABLE 7-10 (Continued)

TYPICAL PROPERTIES OF NYLON 12[9]

(B) ELECTRICAL PROPERTIES

PROPERTY[3]	TEST METHOD	UNIT	STANDARD[1] TYPES
Dielectric Strength	ASTM D 149	V/mil	452
	(Short-time)	V/mil	407[4]
	ASTM D 149	V/mil	409
	(Step-by-step)	V/mil	364[4]
Dielectric Constant	ASTM D 150		
60 cycles[1]			4.17
10[3] cycles[1]			3.82
10[6] cycles[1]			3.14
60 cycles[2]			4.41
10[3] cycles[2]			3.98
10[6] cycles[2]			3.18
Dissipation Factor	ASTM D 150		
60 cycles[1]			0.0422
10[3] cycles[1]			0.054
10[6] cycles[1]			0.0273
60 cycles[2]			0.0475
10[3] cycles[2]			0.0536
10[6] cycles[2]			0.0305
Arc Resistance	ASTM D 495	sec	109[1] (failure by melting)

(C) CHEMICAL RESISTANCE PROPERTIES

CHEMICAL[5]	TEMP, °F	PERCENTAGE INCREASE IN (ASTM D 543)		
		WEIGHT	THICK- NESS	DIAM- ETER
ASTM Fuel B	73	0.35	0.80	0.14
Carbon Tetrachloride	73	0.37	0.80	None
Ethyl Alcohol (50%)	73	1.48	0.79	0.26
Ethyl Alcohol (95%)	73	2.65	1.88	0.24
Ethylene Dichloride	73	1.80	0.81	0.15
2-Ethylhexyl Sebacate	73	−0.03	None	0.05
2-Ethylhexyl Sebacate	302	2.17	1.1	0.4
Gasoline (regular)	73	0.25	None	0.11
Hydrochloric acid (10%)	73	0.37	0.81	0.05
Isooctane	73	0.11	None	−0.05
Kerosene	73	0.10	None	None
Sodium Carbonate (10%)	73	0.39	0.55	0.05
Sodium Chloride (10%)	73	0.42	None	0.05

TABLE 7-10 (Continued)

TYPICAL PROPERTIES OF NYLON 12[9]

(C) CHEMICAL RESISTANCE PROPERTIES

CHEMICAL[5]	TEMP, °F	PERCENTAGE INCREASE IN (ASTM D 543)		
		WEIGHT	THICK-NESS	DIAM-ETER
Sodium Hydroxide (10%)	73	0.42	None	None
Sulfuric Acid (3%)	73	0.44	None	0.05
Toluene	73	0.70	0.80	0.05
Transformer oil	73	0.07	None	0.05
Transformer oil	158	0.14	None	0.05
Trichloroethylene	73	4.20	2.2	0.19
Water, Distilled	73	0.46	None	None
Water, Distilled	158	1.47	None	0.29

[1] Standard Types L1600, L1700, L1700M, L1801, L1801F, L1901, L1901F, L2101, L2101F
[2] Long Term Immersion at 20° C
[3] All samples conditioned by Procedure A, ASTM D 618 (40 hr at 73.4°F and 50% RH)
[4] Conditioned by Procedure D, ASTM D 618 (24 hr immersion in water at 73.4°F)
[5] Two-inch diameter discs of nylon 12 (Type L1801) were immersed in several typical solvents and chemicals for 168 hr at the temperatures indicated. They were wiped dry and measurements were made on weight and dimensional changes.

stiffness, and density increase over a period of 5-7 days, at which time it attains its ultimate properties. As a result of this change, polybutylene exhibits excellent creep resistance and possesses excellent environmental and mechanical stress crack resistance. Shrinkage accompanies the change in crystallinity as shown in Table 7-11. This shrinkage is predictable and can be taken into consideration when designing close tolerance parts[11].

Typical tensile properties for a 75-mil polybutylene rotomolded part are

	Tensile Modulus	Yield Strength	Break Strength	Elon-ga-tion	Dens-ity	MI
PB-630	37,200 psi	2270 psi	3000 psi	314%	0.902	20.4

Typical property data are presented in Tables 7-12, 7-13, 7-14, and Fig. 7-7.

7-9 POLYCARBONATE

Polycarbonate is transparent and tough, has good rigidity, and has high temperature resistance compared to many thermoplastics. The higher resin costs and special processing

precautions have limited the use of this material in rotational molding. The powder must be absolutely dry before molding, and the use of a nitrogen atmosphere is necessary.

7-9.1 RAW MATERIAL PARAMETERS

Generally a −35 mesh particle size is used. However, some evidence indicates that mesh sizes smaller than −35 promote better mold definition, but such finer grinds can be

TABLE 7-11

PERCENT CHANGE IN LINEAR DIMENSIONS OF A ROTOMOLDED PB-1 SAMPLE[11]

TIME, DAYS	L, %	MOLDING CONDITIONS	PART THICKNESS, in.
0	0	600°F 15-1-5 min	0.250
3	0.61	600°F 15-1-5 min	0.250
4	0.79	600°F 15-1-5 min	0.250
5	1.19	600°F 15-1-5 min	0.250
6	1.49	600°F 15-1-5 min	0.250
7	1.68	600°F 15-1-5 min	0.250
11	1.86	600°F 15-1-5 min	0.250
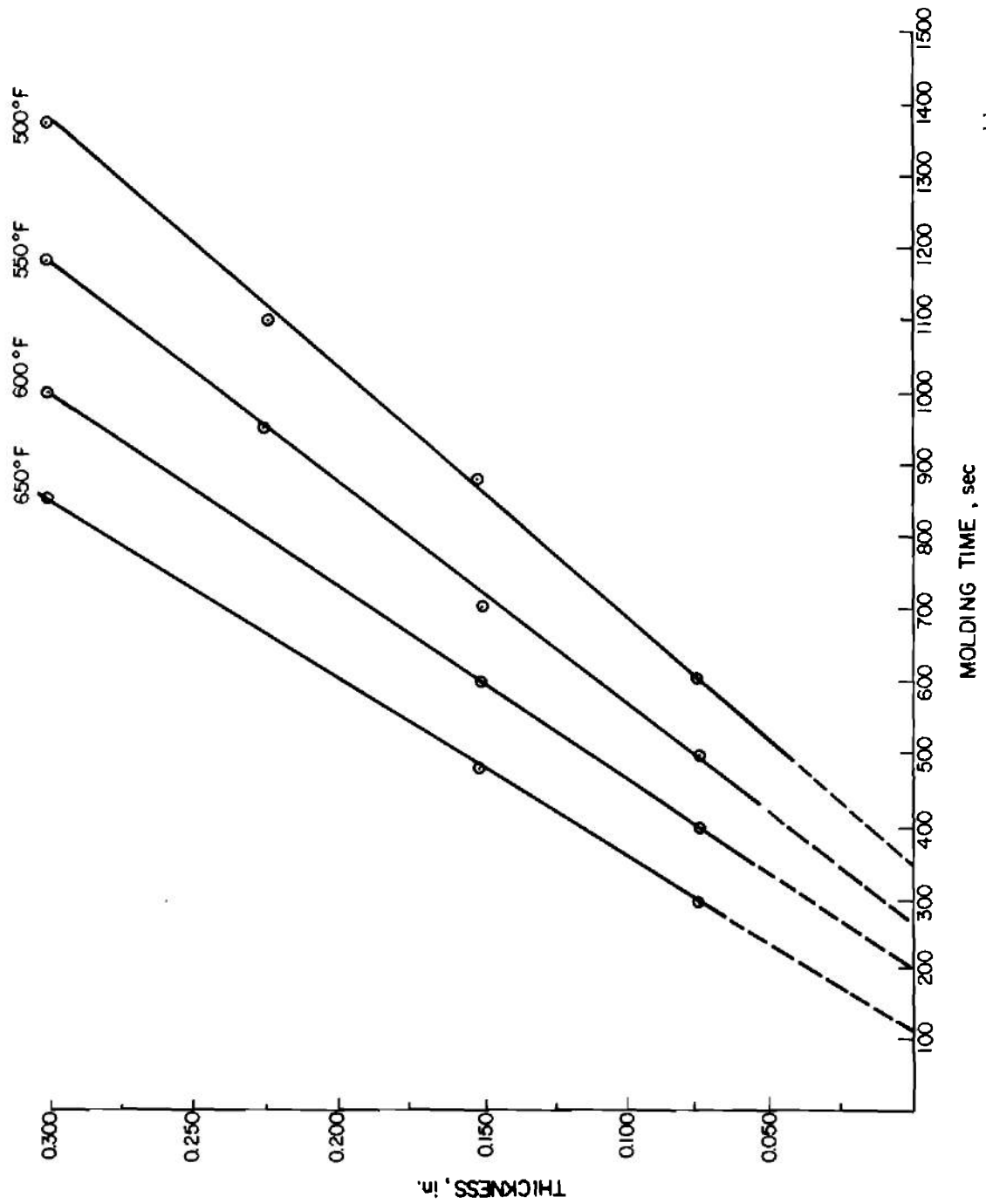
Figure 7-6. Molding Time vs Part Thickness for PB-1 Rotational Molding Resin (20 MI)[11]

TABLE 7-12

TYPICAL PHYSICAL PROPERTIES OF MOBIL POLYBUTYLENE,
ROTATIONAL MOLDING GRADE[11]
(Compression Molded Specimens — Conditioned 10 Days at 23°C, 50% Relative Humidity)

	ASTM METHOD	UNIT	STANDARD TYPES
Density	D1505-63T	g/cm^3	0.91
Melt Index	D1238-57T	—	20
Yield Strength	D638-66T (Die C, 20 in./min)	psi	1900-2200
Tensile Strength	D638-66T	psi	4200
Percent Elongation at Break	D638-66T	%	360
Modulus of Elasticity	D638-66T	psi	35000
Izod Impact Strength	D256-56	ft-lb/in. notch	No break at 73°F 13 at 32°F
Melting Point Range	—	°C	124-126
Softening Point, Vicat	D1525-65T	°C	113
Brittleness Temperature	D746-64T	°C	−18
Shore Hardness	D1706-61	D Scale	53
Environmental Stress Crack Resistance	D1693-60T	—	No failures (2000 + hr)
Dielectric Constant	D-150	—	2.2
Dissipation Power Factor	D-150	—	0.0002

TABLE 7-13

CHEMICAL RESISTANCE TESTS, 7-DAY IMMERSION[11]

PERCENT CHANGE IN

REAGENT	TEMP., °C	TENSILE MODULUS	YIELD STRENGTH	BREAK STRENGTH	WEIGHT	VOLUME
Conc. HCl	65	− 8.15	+ 2.25	− 4.5	0.1	0
Conc. H$_2$SO$_4$	65	− 9.9	+ 0.75	− 16.8	0	0
5% NaClO$_2$	23	+ 2.85	+ 0.75	− 9.65	0	0
5% NaClO$_2$	65	− 13.7	− 3.75	− 13.2	0	0
25% KOH	23	+ 2.2	0	+ 2.2	0	0
25% KOH	65	− 10.5	− 4.5	− 11.3	0	0
#2 fuel oil	23	− 44.2	− 14.3	− 18.3	+ 4.85	+ 2.77

TABLE 7-14

CHEMICAL RESISTANCE OF POLYBUTYLENE RESULTS OF
SIX-MONTH EXPOSURE AT 73°F[11]

CHEMICAL	WEIGHT CHANGE, %	APPEARANCE CHANGE	STRENGTH CHANGE, %
Acids and Bases			
HCl concentrated	+ 0.1	None	+ 1
HCl 1%	+ 0.11	None	None
HNO_3 concentrated	+ 1.9	Attack	− 40
HNO_3 1%	None	None	None
H_3PO_4 concentrated	None	None	None
H_3PO_4 1%	None	None	None
H_2SO_4 concentrated	+ 3.1	Attack	
H_2SO_4 1%	+ 0.1	None	None
NaOH 20%	None	None	None
Solvents			
Acetone	− 0.3	None	None
Benzene	+ 13.5	Swollen	− 22
Ethanol	− 0.3	None	None
Ethyl Ether	− 6.2	Crazed	+ 5
Methanol	− 0.3	None	None
Water	None	None	None
Oils			
Corn Oil	+ 0.3	None	None
Mineral (White) Oil	+ 30	Swollen	
Olive Oil	+ 0.3	None	None
Peanut Oil	+ 0.3	None	None
Silicone Oil	− 0.1	None	+ 5
#2 Fuel Oil	+ 4.9		
Other Chemicals Tested			
Formalin, 36%	+ 0.4	None	None
Hydrogen Peroxide, 3%	+ 0.2	None	None
Igepal, 100%	− 0.6	None	None
Igepal, 1%	− 0.3	None	None

produced only at slower rates with proportionately higher grinding costs.

Suppliers are:

1. General Electric Company[12]

Resin Designation	Description
Lexan® RP 70	General purpose, not UV stabilized

Resin Designation	Description
Lexan® RP703	A general purpose resin with a broad temperature range (−215° to 270°F). It is light, UV stabilized, and rated SE II according to UL Bulletin 94.
Lexan® RP704	Meets Food and Drug Administration approval for food and beverage container applications.
Lexan® RP714	An improved flame resistant grade with all the properties of standard Lexan resin, plus flame resistance. It is UL rated SE I, and rated Class A according to Federal Aeronautics Administration flame resistance specification 29.853.

2. Mobay Chemical Company[13]

Merlon Grade	Melt Flow, g/10 min, ASTM D1238	
5400	12.0 - 24.0	Merlon 5300 is recommended as a general purpose grade. It has an optimum combination of end-use properties and processing characteristics, and should be selected for the initial rotomolding trials when investigating new applications.
5300	6.0 - 11.9	All grades are available in water-white/transparent colors, and grades 5300 and 5200 are supplied in selected opaque colors. UV stabilizer can be added, and FDA requirements can be met.
5200	3.0 - 5.9	

Costs are approximately $1.30 per lb.

7-9.2 PROCESS VARIABLES

7-9.2.1 Drying Cycle

All polycarbonate resins must be predried before molding. For example the moisture content of Lexan® resins should be less than 0.02 percent.

Recommended drying conditions for polycarbonate resins are 2 hr at 250°F in a dehumidifying oven equipped with a desiccant bed. The air in the oven should have a dew point of −20°F or lower. For efficient drying, the resin should be placed in trays not more than 1 in. deep[13]. The oven should be positioned immediately next to the loading station of the machine. By pre-weighing the powder, the time of exposure to the atmosphere between oven and rotomolding machine is held to a minimum. Greater than 1 min exposure time of the dry powder to the atmosphere between oven and machine is undesirable.

Hopper dryers are satisfactory if they are specially designed for powder drying. Units such as the UNA-DYN ⓣ PD line are recommended. Hopper dryers used for pelletized resin are not acceptable[12].

The rotomolding machine oven can be used for drying Merlon powder by placing undried powder in the mold, in the oven, with the inlet air temperature set at 350°F. The 350°F setting is maintained for 5-7 min, then increased to the temperature required for the heating cycle[13].

7-9.2.2 Heating Cycle

Quality of the parts is highly dependent on
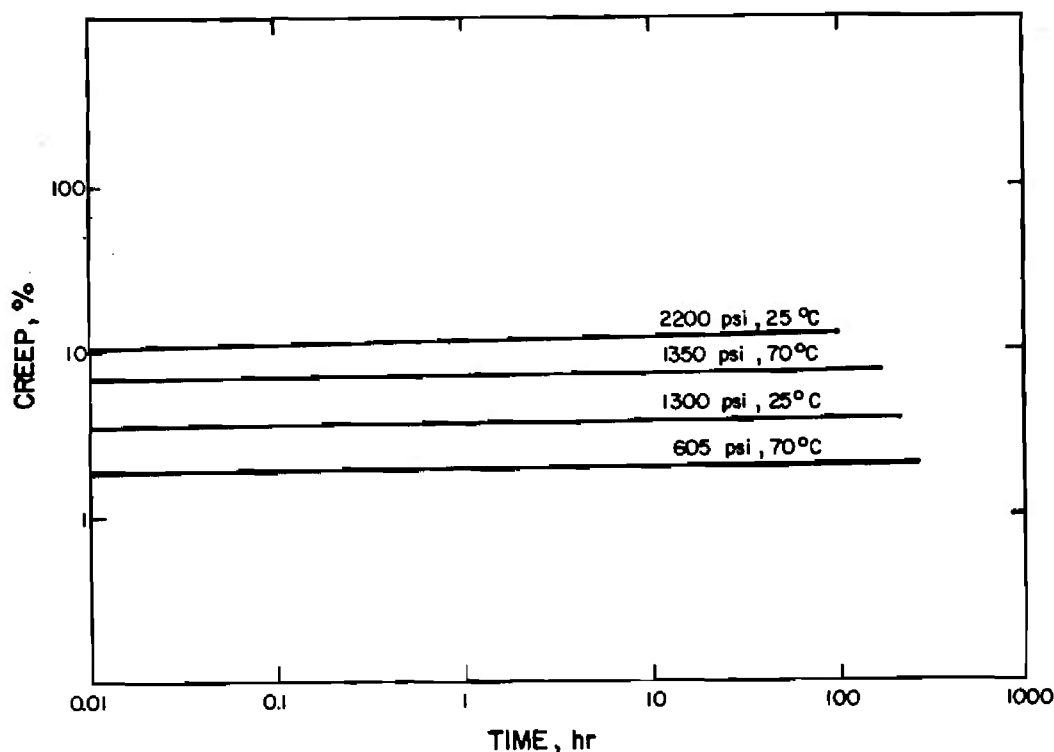
Figure 7-7. Creep Behavior of MOBIL Polybutylene[1 1]
(Note that no significant change occurs
after the initial elongation)

the time-temperature relationship during the cycle. For example, as little as 10 percent change in shot size without altering time and temperature results in parts of significantly different appearance.

For a rule-of-thumb, the recommended time/temperature relationship for start-up is 15 min at 725°F. Generally, cycle times will vary between 10 and 20 min, and temperatures between 575° and 800°F, with rotational speeds of 8-10 rpm. As the oven temperature is reduced, the molding time must be increased. Local molding conditions will dictate the optimum time/temperature relationship for a given part. A few trial runs are usually required before finished parts are produced which meet all design parameters.

Normally, cycle time should be increased at least 25 percent for each 50-75 deg F reduction in temperature from 750°F. For example, a 15-in diameter spherical ball

weighing 3 lb can be molded at 750°F for 8 min or at 700°F for 10 min. At a temperature of 600°F the heating time increases to 14-16 min. Parts with 1/8-in. wall sections are best molded at 725°F for 8 to 10 min. Parts with wall sections under 1/8 in. are best molded at 725°F for 8 min or less[1 2].

Appearance of the parts will suggest what changes, if any, need to be made. A tan appearance means that the parts have been exposed too long at too high a temperature; a cloudy appearance or frosty, rough interior walls indicate that parts have not been exposed to temperature long enough[1 4].

7-9.2.3 Cooling Cycle

Forced air is the primary cooling medium. For operating efficiency, however, the length of the cooling cycle should be identical to that of the preceding heating cycle and, in the case of certain parts, a short water spray of at

least 2-3 min may be desirable at the end of the cooling cycle.

7-9.3 MOLD RELEASE AGENTS

Peninsula Chemical MR-22 bake-on silicone mold release is recommended, but it requires refurbishing three or four times in a normal month of production. Fre-Kote Chemical's Fre-Kote 33 also offers excellent results. When using an aerosol release, enough time must be allowed for the solvent carrier to flashoff the mold surface and out of the cavity. The standard releases approved for use with Lexan® resin are: GE SR475, Dow Corning 230, Zip S-100, and Ram GS-3[12]. Steel molds with a generous draft of about 5 deg require no mold release[14].

7-9.4 EQUIPMENT

In general, the higher the quality of the mold, the better the part. Machined nickel and aluminum are the preferred mold materials, although cast nickel and aluminum also have been used effectively. The interior surface must be scrupulously clean and highly polished to avoid porous molds. Allow generous drafts of at least 3 deg, and corners where the inside radius is less than 0.2 in. should be avoided[12,14].

All molds should be designed with connections permitting purging during the oven and cooling cycles. Molds must be well fitted and constructed so that the mold can be clamped vapor tight around the joining surface at the loading station. Also, machine arms should be drilled to permit an inert gas purge of the mold while maintaining about 20 psig internal mold pressure. Dry nitrogen is suitable as a pressurizing purging medium, and the equipment should include a small rotometer to measure the flow of gas through the mold[14].

7-9.5 PROPERTIES

Tables 7-15 and 7-16 present some typical property data for polycarbonate resins.

7-10 POLYETHYLENE HOMOPOLYMERS AND COPOLYMERS

These materials—low- and high-density polyethylene homopolymers; and ethylene-butene, ethylene-ethyl-acrylate, and ethylene-vinyl acetate copolymers—are the workhorses of rotational molding. They have the greatest range of properties and are processed easily with good flow down to a melt index of 0.8. High-density polyethylene possesses greater strength and rigidity than low density, but it is also more prone to distortion and warpage in molding. Internal cooling is necessary when large flat sections are present in high-density parts. Glass-reinforced low-density polyethylene is also suitable for rotational molding. The glass-containing molded articles approach the rigidity of high-density polyethylene while essentially maintaining the easy moldability of low-density polyethylene.

The ethylene copolymers offer improved flexibility and resilience over a wide temperature range and exhibit high impact strength even at very low temperatures.

7-10.1 RAW MATERIAL PARAMETERS

A 35-mesh particle size is generally satisfactory for both high and low density polyethylene homopolymers and copolymers. However, they are offered with a variety of combinations and wide ranges of melt indexes, densities, and particle sizes. The effects of melt index and density on the end-product properties and processability are quite critical for rotational molding, whereas those of particle size are considerably less. Some of the effects are given in Table 7-17.

The flexible ethylene copolymers differ distinctly from ethylene homopolymers in the relationship of density to stiffness modulus. The stiffness of copolymers decreases as the density increases (see Table 7-17).

Chopped strand fiber glass, preferably 1/8 in. in length, can be used with higher melt index, low-density polyethylene resins in the

TABLE 7-15

PROPERTIES OF NATURAL LEXAN® RP700 RESIN[1][2]

PHYSICAL PROPERTIES

PROPERTY	ASTM TEST	AVERAGE VALUE
Specific Gravity	D792	1.20
Refractive Index at 25°C		1.586
Mold Shrinkage, in.		0.005-0.010
Rockwell Hardness	D785	M70
Abrasion Resistance, Taber abraser with CS-17 wheel	D1044	10 mg/1,000 cycles
Falling Ball Impact, 1 in. dart, ft-lb		60-80
Tensile Strength, psi	D638	9,000
Elongation, %	D638	60
Tensile Modulus, psi	D638	350,000
Tensile Ultimate Strength, psi	D638	9,500
Compressive Strength, psi	D695	12,500
Compressive Modulus, psi	D696	345,000
Flexural Strength, psi	D790	13,500
Flexural Modulus, psi	D790	370,000
Shear-Yield Strength, psi	D732	6,000
Shear-Ultimate Strength, psi	D732	10,000
Light Transmission (1/8 in. thick disc), %		85
Water Vapor Permeability, cm³/STP/mm/sec/cm²/cm Hg		14×10^{-13}
Nitrogen Permeability, cm³/STP/mm/sec/cm²/cm Hg		3×10^{-10}
Carbon Dioxide Permeability, cm³/STP/mm/sec/cm²/cm Hg		80×10^{-10}
Poisson's Ratio		0.37
Modulus of Rigidity	D621	116,000
Deformation Under Load, 4000 psi 77°F, %		0.2
158°F, %		0.3
Fatigue Endurance Limit (Krause Method) 1800 cycles/min, 73°F, 50% RH, psi		1,000
Water Absorption, 24-hr immersion, %	D570	0.15
Equilibrium 73°F, %		0.35
Equilibrium 212°F, %		0.58

THERMAL PROPERTIES

PROPERTY	ASTM TEST	AVERAGE VALUE
Flammability (UL Bulletin 94)	D635	SE-1
Flammability		Self-extinguishing
Heat Deflection Temperature		264 psi: 270°F; 66 psi: 280°F
Mold Shrinkage, in./in.	D648	0.006-0.012
Thermal Conductivity, cal/sec-cm²-(°C/cm)	D955	4.6×10^{-4} ; 3.7×10^{-4}
Btu/hr-ft²-(°F/in.)		1.35
Coefficient of Linear Thermal Expansion −30° to 30°C, in./in.°F	H696	3.75×10^{-5} ; 6.7×10^{-5}
Brittle Temperature, °C	D746	< −135°C
Specific Heat		0.30
Heat of Fusion, cal/g		33 (Winemann): 34.6 (Jones, Karasz & Karasz, O'Reilly, Bain)

ELECTRICAL PROPERTIES

PROPERTY	ASTM TEST	−30°C	−3°C	23°C	100°C	125°C
Dielectric Constant						
60 cycles	D150	3.12	3.14	3.17	3.15	3.13
10⁶ cycles	D150			2.96		
Power Factor						
60 cycles	D150	0.005	0.004	0.0009	0.0009	0.0011
10⁶ cycles	D150			0.010		
Volume Resistivity, ohm-cm		$> 10^{17}$	$> 10^{17}$	21×10^{16}	2.1×10^{15}	2.7×10^{14}
Arc Resistance, Stainless-steel Strip Electrodes, sec	D495			10-11		
Tungsten Electrodes, sec				120		

PROPERTY	ASTM TEST	25°C	100°C
Dielectric Strength short time	D149	3,910 V/mil at 1.5 mils; 3,080 V/mil at 3.0 mils; 2,560 V/mil at 4.7 mils; 1,130 V/mil at 23 mils; 380ₐ V/mil at 125.0 mils	3,380 V/mil at 3.0 mils; 1,250 V/mil at 23.0 mils; 600ₐ V/mil at 125.0 mils
Resistance to Electron Beam Radiation		No change up to 5×10^{7} rads dosage	

(ₐThe step-by-step values are essentially the same as the short-times values for the 125-mil piece.)

TABLE 7-16

PROPERTIES OF MERLON 5300 POLYCARBONATE RESIN[13]

PROPERTY	ASTM METHOD	VALUES
Specific Gravity	D792	1.2
Tensile Strength:	D638	
Yield		8000-9500 psi
Ultimate		9000-11,500 psi
Elongation:	D638	
Yield		7-9%
Ultimate		100-130%
Flexural Modulus	D790	$3.2\text{-}3.5 \times 10^5$ psi
Impact Strength, Notched Izod, 1/8-in. Specimen	D256	12-17 ft-lb/in.
Heat Distortion Temp/264 psi	D648	265°-285°F
Light Transmission	D1003	85-88%
Flame Resistance	D635	Self-extinguishing
Temperature Use Range		-150° to +250°F

TABLE 7-17

EFFECT OF INCREASES IN MELT INDEX AND DENSITY OF POLYETHYLENE POWDER ON PROPERTIES[15]

	MELT INDEX INCREASE	DENSITY INCREASE
Melting point	decreases	increases
Flow	increases	
Impact strength	decreases	decreases
Stiffness		increases
Vicat softening temperature	decreases	increases
Resistance to low-temperature brittleness	decreases	decreases
Barrier properties		increase

rotational molding process. Satisfactory moldings can be produced at about 8 percent glass in complex molds, and up to 15 percent glass in simple molds. Predispersion of the glass in the polyethylene powder is necessary to achieve maximum interior surface smoothness. The higher melt index resins provide lower melt viscosity and some degree of flow during the molding cycle. This allows the glass strands to "lay-over" into the molten polymer and be covered sufficiently to present a smooth, uniform interior surface. The lower melt index and higher density resins do not exhibit this ability[16].

Table 7-18 shows the effect of glass lengths on interior wall surface and mold fill out in a complex mold with PEP-400 polyethylene (0.924 density, 27 melt index).

TABLE 7-18

EFFECT OF GLASS LENGTH AND LOADING ON ROTATIONAL MOLDING[16]

GLASS LENGTH, in.	INTERIOR WALL SURFACE GLASS LEVEL, %			MOLD FILL OUT GLASS LEVEL, %	
	5	10	15	5	10
1/32	OK	OK	OK	OK	OK
1/8	OK	OK	Rippled	OK	Slight Bridging
1/4	OK	Rippled	Unacceptable	Bridging Poor Fill Out	—

Some of the resin suppliers are:

1. Phillips Petroleum Co:

Marlex® Resin Number	Density	Melt Index	Description
*TR-955	0.955	6.5	Copolymer, excellent processability
*TR-980	0.955	18.0	Copolymer, outstanding processability
TR-960	0.964	6.5	Excellent surface appearance

2. Gulf Oil Chemical Co:

Poly-eth Resin Number	Density	Melt Index	Description
3003	0.922	2.0	High impact strength and excellent stress crack resistance
LR 3807	0.964	6.5	High impact strength and exceptionally high stiffness

*Ethylene-butene copolymer

3. E. I. du Pont de Nemours & Co., Inc:

ALATHON® Resin Number	Density	Melt Index	Description
1724	0.916	12	Homopolymer containing slip; good processing characteristics
1730	0.922	6	Moderate rigidity and toughness
2005	0.919	1.9	Outstanding toughness and stress crack resistance
7440	0.940	4	Copolymer, toughness and stress crack resistance
7140	0.950	4.5	Copolymer, good toughness, lower warpage
7040	0.960	6	Maximum stiffness and dimensional stability. Good toughness
8140	0.950	4.2	Superior impact strength
8043 BK011	0.962	6	Meets FDA Food Additive Regulations

4. Union Carbide Corp:

PEP

Resin Number	Density	Melt Index	Description
231	0.919	10	Good low temperature impact
315	0.919	10	Good low temperature impact, surface characteristics and mold release
326	0.923	1.15	Good stress crack resistance, low temperature impact
530	0.924	9	Good surface characteristics and toughness

5. U. S. I. Chemicals Corp:

Microthene®

Resin Number	Density	Melt Index	Description
MC10-734	0.915	22	White pigmented
MK08-256A	0.953	5	High stiffness, excellent impact strength, resistance to weathering, good toughness
MN701	0.912	70	Low stiffness, high flow characteristics
MN703-06	0.917	1.2	Very high toughness, low stiffness, contains antioxidant
MN706	0.923	22	High resistance to moisture and chemicals
MN710-20	0.916	22	Contains slip additive
MN711-20	0.914	22	Contains slip additive
MN714	0.912	70	High flow characteristics
MN718	0.915	8	Low stiffness
MN720	0.915	12	Low stiffness
MN721	0.924	5	Medium to low stiffness
MN722	0.924	5	Medium to low stiffness
MN751	0.924	8	Good toughness, low stiffness
MN754-18	0.924	12	Outstanding processability
**MU763	0.928	9	High stiffness, toughness and impact strength

Microthene® Resin Number	Density	Melt Index	Description
**MU760	0.941	20	Good flexibility, adhesion, low temperature resistance
MA778	0.949	6	High stiffness, good toughness

**Ethylene-vinyl acetate

Costs are approximately $0.26 per lb.

7-10.2 PROCESS VARIABLES

7-10.2.1 Drying Cycle

None.

7-10.2.2 Heating Cycle

Oven temperatures range from 550° to 700°F. Temperatures of 650°F have been reported to be satisfactory for molding most high-density polyethylenes in hot air ovens. Generally, the larger and more sophisticated operators use the higher temperatures because cycle times can be reduced. However, with high oven temperature, control must be more accurate to avoid overheating the resin.

Heating times, of course, vary with oven

temperature, part thickness, and the kind of resin used. Commercial cycles may vary from 5 to 20 min. High-density polyethylene usually requires 10-20 percent more heating time than low-density polyethylene for the same part.

It was found that an oven cycle 1 to 2 min longer than that needed for the straight low density resin was required to form, fuse, and fill out glass containing low-density polyethylene parts[16].

The effect of wall thickness on heating time for high- and low-density polyethylene is shown in Fig. 7-8.

The effect of heating time on impact strength is illustrated in Fig. 7-9. A series of
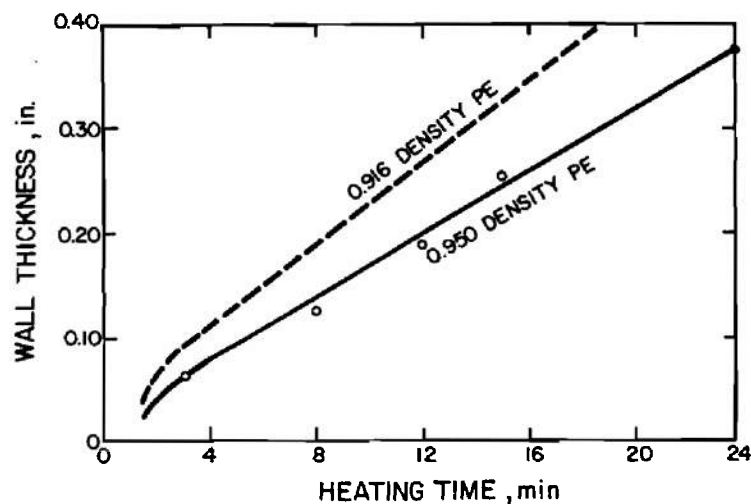
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Figure 7-8. Effect of Wall Thickness on Heating Time[32]
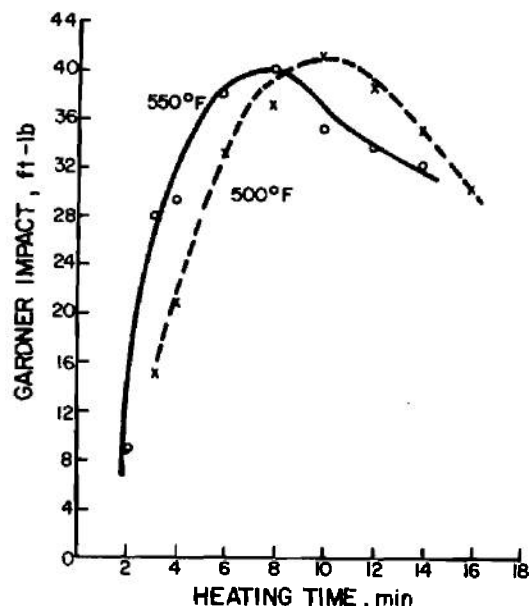
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Figure 7-9. Effect of Heating Time on
Impact Strength of 0.95 Density PE[32]
(Melt Index 5 g/10 min)

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Figure 7-10. Effect of Heating Time on
Melt Index of 0.95 Density
PE[32]

1/8 in. thick parts was molded at the indicated heating period using molten salt spray equipment at 550°F. Flat panels were cut from each molding and tested with a constant height, falling weight impact tester at −20°F. The program was repeated using parts molded at 500°F to show the influence of molding temperature.

The effect of heating time on melt index is shown in Fig. 7-10.

Discoloration and odor can be eliminated by flushing the air out of the mold with an inert gas, such as nitrogen or carbon dioxide. The mold is purged before the heating process is started. The gas flow rate will depend upon the size of the mold. A flow rate of 10 to 15 cfm for 30 sec is sufficient for a mold volume of 1 ft³. If the gas flow is continued during heating, it tends to have a cooling effect on the resin, and upsets the previously established heating time. As the mold heats up, a pressure is created inside the mold, which keeps air from returning. The inert gas is turned on again during cooling. A low molecular weight film will still be present on

the inner surface of the molding, but will add no color or odor to the part. Table 7-19 indicates some results of inert purging.

7-10.2.3 Cooling Cycles

Due to the design of most rotational molding machines, cooling cycles equal heating cycles. Quite often, the cooling cycle will be in two phases: an initial cooling in air, followed by a water spray. The air cooling may be approximately one-third of the total available cooling time and is helpful in

TABLE 7-19

EFFECT OF INERT ATMOSPHERE[32]
(0.95 Density, 5.0 Melt Index PE)

	NITROGEN	AIR
Impact Strength (Gardner), ft-lb/0.125 in. at −20°F	40	37
Stress Crack Resistance, hr/F$_{50}$	2.9	1.9

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reducing warpage particularly with high-density material.

High-density polyethylene parts generally are cooled with a highly atomized water spray on the rotating mold. Rapid cooling is desirable to obtain the best physical properties. However, if the water is applied too vigorously, warpage or localized brittleness may result. In practice, control of warpage dictates how fast a part can be cooled.

One way to obtain rapid and uniform cooling is to use a combination of external and internal cooling. Cooling the polymer from both sides not only increases the rate, thus improving the physical properties, but gives better dimensional control by promoting uniform shrinkage. The same arrangement for inert gas may be used for internal cooling. Cooling time can be cut in half by passing chilled air or water vapor through the mold. Liquid carbon dioxide also has been used. As the liquid passes through an orifice in the mold, it changes phase and absorbs heat from the hot polymer. A thin wall part can be cooled in a matter of seconds by this method.

Shrinkage is unusually hard to predict in rotational molding. High-density polyethylene will shrink from 1.5 to 3.5 percent, depending upon the density and melt index of the resin, the shape of the part, and the release characteristics of the mold. The most significant factor, however, is cooling; the highest shrinkage is found in slowly cooled parts. This is to be expected, since the molded density is higher. Parts with an interrupted surface tend to shrink less than smooth flat parts. The shrinkage on one long slender tank with transverse corrugations was 1.85 percent over the long dimension. At right angles, or parallel to the corrugations, the shrinkage was 2.4 percent. For mold construction purposes, a shrinkage factor of 2.5 percent normally is used for high-density polyethylene.

7-10.3 MOLD RELEASE AGENTS

Low-density polyethylene requires a release

agent with excellent release effectiveness; high-density polyethylene does not. For example, if a very effective release agent is used on the mold with high-density polyethylene and then the mold is cooled in the manner normally used for low-density polyethylene, bad warpage occurs. This warpage is caused by the item releasing partially from the mold wall while it is still quite hot.

Variables such as the mold type, mold finish, part configuration, and the particular density resin used will affect the release characteristics. The release agent selected and the technique of application, if it affects the release characteristics, should be chosen so that the part releases at a relatively low temperature. Properly used release agent along with controlled uniform cooling will go a long way toward eliminating part warpage for high-density polyethylene.

Zinc stearate powder provides a temporary mold release for high-density polyethylene. It is applied by dusting or spraying onto the mold surface every second or third part. The release effectiveness depends somewhat upon the amount applied to the mold; this does not change the life, however. This method has not been recommended because of its short life, its adverse effect on part impact strength, and the fact that it reduces adhesion of labels and causes decorating problems. Also, tests at elevated temperatures have indicated that it may promote surface crazing and stress cracking of high-density polyethylene parts which could cause premature failure of molded parts in actual service[17]. However, it has been reported[18] that dry-blending approximately 1/20 percent of calcium or zinc stearate powder into the material was sufficient to produce good parts. In sufficient quantities, stearates may become an embrittlement agent as previously mentioned, but in these concentrations no significant embrittlement has been found.

Semipermanent mold release agents based on fluorocarbon resins, silicone resins, or other high temperature resins generally are

TABLE 7-20

COMPARISON OF LOW- AND HIGH-DENSITY POLYETHYLENE PROPERTIES[17]

PROPERTY	LOW DENSITY	HIGH-DENSITY ETHYLENE HEXENE COPOLYMER	HIGH-DENSITY HOMOPOLYMER
Density, g/cm^3 ASTM-D1505-63T	0.924	0.952	0.962
Melt Index	3.8	2.4	2.7
Heating Time 650°F	11 min	12 min	13 min
Tensile Strength, psi (20 in./min) ASTM-D638-64T	1300	3700	4000
Elongation, % (20 in./min) ASTM-D638-64T	250	35	24
Tensile Tear, lb/0.001 in. ASTM-D1004-66	0.40	0.90	0.90
Impact Strength, ft-lb (Dart Drop)	30	40	40
0.125 in. thick parts	—	—	—

applied to the mold. Care should be taken to insure that only silicone solutions are recommended and never silicone emulsions which adversely affect stress crack resistance. When properly applied and cured, these may be effective from about 50 to several hundred releases per application[19]. Since there is very little transfer of release agent to the part, the ability of the part to take decorating treatment should not be affected.

Several commercial compounds that have proven satisfactory are C.P. Hall's MR-22 and Dow Corning's R-671 two heat curing semipermanent type silicones; and Dow Corning's DC20, High-temp Mold Release, Du Pont's "Vydax AR", and General Mills Release Agent H-15-1[20].

7-10.4 PROPERTIES

The physical properties of the various polyethylene resins vary because of differences in molecular weight, molecular weight distribution, melt index, copolymerization, glass reinforcement, and other factors. These account for differences in the maximum impact strength, toughness, moldability, and optimum heating cycle. In general, resins of 1 to 6 melt index, which border on the lower limit of processability, tend to have the best impact strength and toughness. Resins of 10 to 20 melt index possess better moldability than those of 1 to 6 melt index, and frequently are used where moldability is more important than impact strength.

Table 7-20 compares general values of the physical properties of high-density homopolymers and high-density ethylene hexene copolymers of approximately the same melt index with a low-density resin. These data show that the high-density resins

TABLE 7-21

POLY-ETH 3003 AND LR3807 POLYETHYLENE POWDER
(GULF OIL CHEM. CO.)[21]

PROPERTY	ASTM TEST METHOD	TYPICAL AVERAGE VALUE 3003	TYPICAL AVERAGE VALUE LR3807
Resin			
Melt Index, g/10 min	D1238-65T	2.0	6.5
Density, g/cm^3	D1505-63T	0.922	0.964
Color	—	Natural	Natural
Particle Size, mesh	U.S. Standard	35	35
Compression Molded Samples			
Brittleness Temperature, °F	D746-64T	− 40	< − 180
Softening Point, Vicat, °F	D1525-65T	200	257
Yield Strength, psi	D638-64T	1,600	—
Tensile Strength, psi	D638-64T	1,600	4,000
Elongation, %	D638-64T	500	280
Stiffness in Flexure, psi	D747-63	25,000	140,000
Hardness, Shore "D"	D1706-61	50	68
Environmental Stress Crack Resistance	D1693-66	Very Good	Good

are much stiffer, have much higher tensile strength, and have much higher tensile tear strength than low-density polyethylene. Low-density polyethylene has considerably greater elongation when measured at 20 in./min. In addition to increasing stiffness, increasing the density raises the melting point, permits higher service temperature limits, and improves barrier properties of the end product.

Some typical property data are listed in Tables 7-21, 7-22, and 7-23.

Table 7-24 contains some typical properties of ethylene copolymers.

Table 7-25 compares the effect on physical properties of the three fiber lengths at various levels in PEP-440. The data clearly demonstrate that the rigidity, tensile strength, and yield and tear strength increase as the level and length of the glass fiber increases.

Table 7-26 compares the physical properties of samples which had been molded

from powder into which the glass had been hot compounded rather than dry blended. The data reveal that the addition of glass by dry blending results in properties superior to those obtained when the glass is added by hot compounding. This is attributed to the fact that, in the case of hot compounding, the glass fiber length is reduced by the subsequent pulverizing operation. Maximum reinforcement is obtained when longer fibers are present in the molded part[16].

Fig. 7-11 compares the cooling rate on shrinkage of various polyethylene resin systems.

7-11 CROSSLINKED HIGH-DENSITY POLYETHYLENE

Crosslinked polyethylene has excellent impact strength, tensile creep resistance, tear strength, and exceptional stress cracking resistance. The stress cracking resistance and tensile creep resistance of parts far exceed that of all other noncrosslinkable HDPE rotational molding resins. The crosslinked

TABLE 7-22

PROPERTIES OF ALATHON® RESINS[2,2]

ASTM TEST METHOD	PROPERTY[1]	UNITS	LOW-DENSITY			MEDIUM-DENSITY		HIGH-DENSITY		
			1724	1730	2005	7440	7140	7040	8140	8043 BK 011
D1505	Density	g/cm³	0.916	0.922	0.919	0.940	0.950	0.960	0.950	0.962²
D1238	Melt Index	g/10 min	12	6	1.9	4	4.5	6	4.2	6
D790³	Flexural Modulus	kpsi	26	38	34	100	153	179	138	146
D1708	Tensile Strength (0.5 in./min)	psi	1400	1700	2200	3000	3700	4000	3400	3400
D1708	Elongation (0.5 in./min)	%	300	400	500	800	1200	>1200	1200	1000
D2240	Hardness	D scale	43	48	48	59	62	65	62	63
D746⁴	Brittleness Temperature	°F	-139	-139	-141	-139	-134	-128	-134	-123
D1693⁵	Stress Crack Resistance (F₅₀)*	hr	<1	<1	140	18	4	2	18	3
D1525	Vicat Softening Temp.	°F	191	206	206	252	262	266	255	261
D648⁶	Heat Deflection Temp.	°F	116	116	122	140	165	163	149	160

ALATHON RESINS

[1] Samples for physical test specimens (except density and melt index) were prepared by compression molding and cooled at a rate of 27 deg F/min.
[2] Density with carbon black added.
[3] 2-in. span, cross head speed 0.05 in./min, 1/8 in. thick.
[4] Procedure A, exposure 5 min, 75 mil thick specimen.
[5] Dry Igepal, low density 125 mil thick specimens, medium and high density 75 mil thick specimen.
[6] 66 psi, 1/8 in.
* = 50% failure.

TABLE 7-23

PROPERTIES OF MICROTHENE® RESINS[2,3]

PROPERTY	TEST PROCEDURE	MN701	MN703-06	MN706	MN710-20	MN711-20	MN714	MN718	MN720
Melt Index, g/10 min	ASTM-D1238-62T	70	1.2	22	22	22	70	8	12
Density, g/cm^3	ASTM-D1505-63T	0.912	0.917	0.923	0.916	0.914	0.912	0.915	0.915
Particle Size, mesh	US Standard Sieve Screening	35	50	20	50	35	50	35	35
Vicat Softening Temperature, °C	ASTM-D1525-58T	80	95	99	85	83	80	88	87
Crystalline Melt Point, °C	Visual	102	—	112	107	107	102	—	—
Tensile Strength:	ASTM-D638-64T (with D412 specimen)								
Yield, psi		1,210	1,400	1,880	1,250	1,250	1,210	1,350	—
Break, psi		1,050	2,000	1,360	1,250	1,350	1,050	1,600	1,425
Elongation, %		280	560	120	460	500	280	550	540
Torsional Stiffness, psi	ASTM-D1043-61T	24,700	25,100	35,100	21,000	19,300	24,700	22,500	25,000
Stiffness in Flexure, psi	ASTM-D747-63	16,600	19,500	82,900	17,400	18,700	16,600	14,100	18,100
Low-temperature Brittleness, °C/F$_{50}$*	ASTM-D746-57T	−34	<−76	−51	−56	−64	−34	<−76	−65
2% Secant Modulus of Elasticity, psi	ASTM-D638-64T	25,400	20,000	29,200	16,000	—	25,400	—	—
1% Secant Modulus of Elasticity, psi	Calculated from 2% value	29,210	23,000	33,570	18,400	19,000	29,210	20,200	20,500
Hardness, Shore "D"	ASTM-D1706	—	—	—	—	41	—	—	—
FDA Requirements	Meets (M); Not Recommended (NA)	NA	NA	M	M	M	NA	M	M

*50% failure

TABLE 7-23 (Continued)

PROPERTIES OF MICROTHENE® RESINS[2,3]

PROPERTY	TEST PROCEDURE	MN721	MN722	MN751	MN754-18	MU763	MA778	MC10-734	MK08-256A
Melt Index, g/10 min	ASTM-D1238-62T	5.0	5.0	8.0	12.0	9.0	6.0	22	5.0
Density, g/cm^3	ASTM-D1505-63T	0.924	0.924	0.924	0.924	0.928	0.949	0.915	0.953
Particle Size, mesh	US Standard Sieve Screening	35	50	35	35	35	35	50	35
Vicat Softening Temperature, °C	ASTM-D1525-58T	100	100	97	96	77	123	85	126
Crystalline Melt Point, °C	Visual	–	–	–	–	–	–	107	129
Tensile Strength:	ASTM-D638-64T (with D412 specimen)								
Yield, psi		–	1,930	–	–	–	–	–	–
Break, psi		1,520	1,530	1,460	1,240	1,700	3,620	1,250	3,600
Elongation, %		470	400	300	70	700	350	460	25
Torsional Stiffness, psi	ASTM-D1043-61T	34,600	39,000	35,900	35,000	14,000	108,000	21,000	–
Stiffness in Flexure, psi	ASTM-D747-63	28,500	34,300	30,900	34,000	–	–	17,400	–
Low-temperature Brittleness, °C/F$_{50}$*	ASTM-D746-57T	<–76	<–76	<–76	<–76	<–76	<–76	–56	–
2% Secant Modulus of Elasticity, psi	ASTM-D638-64T	–	29,000	–	–	–	–	–	–
1% Secant Modulus of Elasticity, psi	Calculated from 2% value	30,150	33,350	33,600	34,000	11,000	101,000	18,400	97,300
Hardness, Shore "D"	ASTM-D1706	–	–	–	–	39	–	–	61
FDA Requirements	Meets (M); Not Recommended (NA)	–	M	M	M	M	M	NA	–

*50% failure

TABLE 7-24

TYPICAL PHYSICAL PROPERTIES OF ETHYLENE COPOLYMERS[24]

		TYPICAL VALUES	
PROPERTIES	ASTM TEST METHOD	20% VINYL ACETATE	28% VINYL ACETATE
Melt Index, g/10 min	D1238	25	25
Density, g/cm^3	D1505	0.940	0.950
Hardness, Shore "A"	D676	88	85
Tensile Strength, psi	D412	2160	2000
Ultimate Elongation, %	D412	750	750
Secant Modulus, psi	D638	4700	3480
Brittleness Temp., T_{50}, °C*	D746	− 78	− 100

*The temperature at which 50% of the number of samples tested show failure.

part behaves as a thermosetting resin. It softens at temperatures similar to that of conventional resins but does not melt at 400°F or higher.

When properly pigmented and UV stabilized, its weathering characteristics are similar to or slightly better than the high molecular weight resins used for extrusion, blow molding, or injection molding[25].

7-11.1 RAW MATERIAL PARAMETERS

A particle size of 35 mesh is recommended for crosslinkable polyethylene powder. An antioxidant and active peroxide usually are added to ensure thermal stability during processing and optimum curing results.

Color compounds give the best pigment dispersion without significant loss of impact strength. Pigments that do not retard the crosslinking must be used.

Dry blends are possible, but they usually are not recommended since many pigments can drastically retard the crosslinking and most molders do not have proper facilities for testing to determine the effect of the pigments.

Crosslinked polyethylene suppliers are

1. Phillips Petroleum Co.—Marlex®

CL-100

2. Raychem Corp.—Flamolin 711

3. USI Chemicals Co.—Microthene® MX1100

Costs are approximately $0.37 per lb.

7-11.2 PROCESS VARIABLES

7-11.2.1 Heating Cycle

Generally, an oven temperature between 550° and 625°F should be used. However, exceptions on either side of this range have been made. Temperatures below 550°F can be used quite satisfactorily but longer cycle times are required. In many commercial ovens, temperatures above 625°F tend to generate too rapid a decomposition of the crosslinking agent. This can cause bubbles in the wall, blow holes through the wall, pock marks on the surface, rough inside surface, or over-pressuring of the mold if adequate venting is not provided[19].

Oven residence times required to "thermally crosslink" high-density polyethylenes are approximately twice those required for normal fusion. These times may vary from 9-13 min depending on the mold, part wall thickness, and oven input temperature. For this reason, proper

TABLE 7-25

PERFORMANCE OF FIBER GLASS IN PEP-440 (0.924 DENSITY, 27 MELT INDEX) POLYETHYLENE[16]

GLASS		TEAR STRENGTH, lb/in.	SECANT MODULUS, psi	TENSILE STRENGTH, psi	ULTIMATE ELONGATION, %	YIELD STRENGTH, psi	FLEXURAL STRENGTH, psi	FLEXURAL MODULUS, psi
%	LENGTH, in.							
0		555	28,000	1540	195	1260	1340	34,400
5	1/32	490	–	1640	70	1400	1580	43,500
5	1/8	625	43,500	1660	40	1440	1730	63,400
5	1/4	645	47,200	1700	20	1500	2370	72,500
10	1/32	475	–	1710	45	1490	1830	64,000
10	1/8	660	53,800	1780	20	1660	2300	76,800
10	1/4	735	69,700	1860	5	1860	3070	106,000
15	1/8	725	73,500	1980	10	1950	2950	98,400

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TABLE 7-26

HOT PROCESSED SAMPLE VS DRY BLEND[16]

%	LENGTH, in.	MIXING METHOD	TEAR STRENGTH, lb/in.	TENSILE STRENGTH, psi	ULTIMATE ELONGATION, %	YIELD STRENGTH, psi	FLEXURAL STRENGTH, psi	FLEXURAL MODULUS, psi
0	—	—	555	1540	195	1260	1340	34,400
10	1/4	Dry Blend	735	1860	5	1860	3070	106,000
10	1/4	Hot Processed	670	1300	60	1230	1450	38,000

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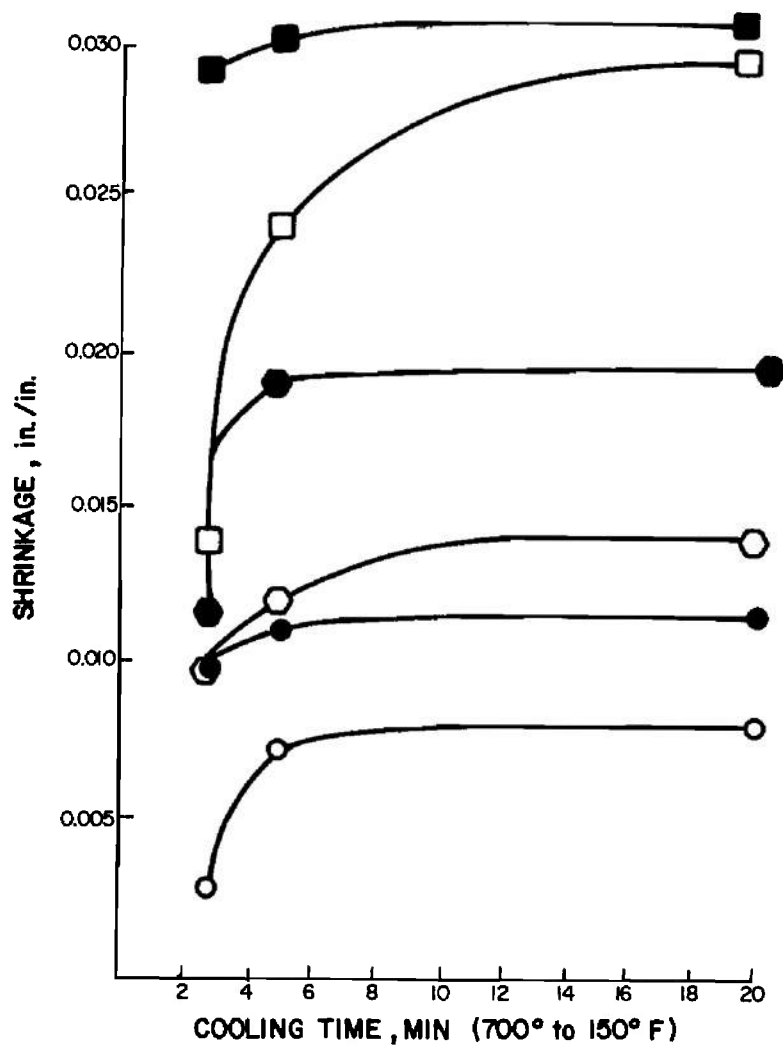
LEGEND:

■ CROSS LINKABLE POLYETHYLENE

● CROSS LINKABLE WITH 5% GLASS

● CROSS LINKABLE WITH 10% GLASS

□ LINEAR POLYETHYLENE (DYLAN 5440)

○ LINEAR POLYETHYLENE WITH 10% F/G

○ LINEAR POLYETHYLENE WITH 5% F/G

Figure 7-11. Effect of Cooling Rate on Shrinkage of Rotomolded Thermoplastics[33]

temperature and cycle time must be established for a given part on each individual machine. The Low Temperature Impact Test and the Bent Strip Test are good methods for checking the cure.

7-11.2.2 Cooling Cycle

Air cooling followed by water spray, which gives uniform coverage of the mold, is required to produce warp-free parts. Also, internal pressure during the cooling cycle helps to prevent warpage.

Inert gas injection should be used during the cooling cycle to flush a large portion of the products of decomposition of the crosslinking agent from the molded part. This is accomplished by introducing an inert gas at low pressure through rotary unions and a drilled spindle into the mold. The mold is then vented on opposite sides with several vents that are open to atmospheric pressure in the cooling chamber. The exhaust fan then removes these gases from the work area. To prevent the possibility of generating a combustible mixture during purging of the mold, an inert gas should be used instead of air.

7-11.2.3 Molding Precautions

Crosslinkable resins contain a crosslinking agent that emits small amounts of pyrolytic products during molding. The molding powder and the emitted vapors may produce skin, eye, and nasal irritation to the operator. For these reasons the following procedures should be observed during molding:

"Operators in a molding plant are exposed to the finely divided molding powder and a small amount of vaporous and liquid decomposition products arising from the additive present in the resin and formed when the molding powder is heated.

"1. If the molding process produces an enclosed item which entraps the decomposition products in its interior, a

vacuum lance should be provided so that the operator can sweep out any decomposition products as the molded item is released. In addition, it is possible to sweep a large portion of the decomposition products from the part during the cooling cycle by introducing inert gas in the part from one side and exhaust through a vent or vents from other sides.

"2. Molding of large, open-sided concave surface items should be conducted in molding equipment enclosed with an exhaust ventilated booth. The ventilation rate should be adequate to prevent the escape of vaporous substances into the operator's environment. A vacuum lance should be provided to sweep out any decomposition products inside the fabricated item as it is released from the mold.

"3. The operators involved in the rotational molding process should wear freshly laundered work clothing daily either in the form of a cover-all or else as a shirt and trousers combination. A light fabric cap and impervious protective gloves should also be worn by the operators. If physical contact between the molded item and the operator's body is required to remove the item from the mold, an impervious apron should be worn by the employee. At the end of the work day, a cleansing shower should be taken before the employee changes into his street clothing"[19].

7-11.3 MOLD RELEASE AGENTS

Too effective a release will cause warpage and pock marks. Several of the silicone mold releases and the fluorocarbon sprays have been used with Marlex® CL-100 and CL-50. Most of the silicones have to be diluted with solvent to get the release properties desired. The fluorocarbon releases can be used with molds that have good draft and require only a slight degree of release. To apply the fluorocarbon without causing warpage or pock marks requires considerable experience. Each individual mold may require a slightly different degree of release. Maintaining

internal pressure by injection of an inert gas such as nitrogen during the cooling cycle allows a wider range of mold release effectiveness to be tolerated on any individual mold.

Molders have had good success with Fre-Kote 33. For flat surface, large radii and highly tapered areas, or any area requiring less effective release, Fre-Kote 32 and 31 can be used. Fre-Kote 32 and 31 both are less effective than 33 with 31 being the least effective. Ram GS-3 also gave excellent results.

The release on molds having complex shapes can be controlled by using different releases on various areas of the mold. Core areas requiring good release can be coated with an effective release while flat sections where poor release is desired can be coated with less effective release. With bake-on releases this technique has been successful. When changing from one mold release to another, especially to the Fre-Kote type, all old release should be removed from the mold. Most of the time this requires scrubbing with steel wool and an abrasive powder. On some fabricated aluminum and steel molds a light grit blast could be used to remove the old release[19].

7-11.4 PROCESS EQUIPMENT

High quality porosity-free molds constructed by any of the conventional methods can be used. For easy part removal a taper of 6 to 8 deg is recommended[19]. All molds must be adequately vented to handle the decomposition gases which can cause a pressure buildup in the mold. To prevent mold damage in cases where vents are not adequate or become plugged, the mold should be designed to withstand several pounds of pressure or be provided with some method to prevent over-pressuring.

Multiple large vent tubes that are placed deep into the part are less likely to become plugged. These vent tubes should have a small amount of fiberglass insulation packed lightly into the end to prevent powder from flowing down inside the tube where it can melt and block the tube.

If internal pressure is used during the cooling cycle, the tubes and rotary unions must be kept open. "In addition, on machines where a regulator controls the pressure applied during the cooling cycle, there should be a pressure relief valve placed between the output of the regulator and the mold vent tube. This relief valve should be set to relieve at a pressure just above that pressure desired to be maintained in the mold. It is possible that pressure can continue to build up in the mold during the cooling cycle until the plastic temperature falls off considerably. In molds with large volumes and cross-sectional areas, significant forces can be generated. For example, with internal pressure of only 6 psig in a mold 36 in. X 36 in. a force of almost 7800 lb is being exerted on the mold surface[19]".

Also, to further reduce the possibility of excessive pressure buildup, the mold parting line should be clamped with spring loaded devices. This allows the mold halves to separate slightly and relieve excess pressure before damage to the mold can occur.

Another method of relieving an unusual pressure buildup is to incorporate a thin section that had been scored in an "X" fashion to perform as a rupture disk. Design of such a disk would require trial and error work to determine the proper thickness and depth of scoring. It would also require shielding with material such as several screen wire layers to prevent increased part wall thickness at the thin section. Fastening of inserts in molds should be done in such a manner that gases or steam generated behind the inserts are relieved to the outside of the mold.

TABLE 7-27

TYPICAL PHYSICAL PROPERTIES OF MICROTHENE® MX 11000[23]

PROPERTY	ASTM TEST PROCEDURE	VALUE
Density, g/cm³ *	D1505	0.940
Particle Size, mesh	US Standard Sieve Screening	35
Tensile Strength at 2 in./min	D638 (with Type IV specimen)	
Break, psi		3,000
Elongation, %		450
Stiffness in Flexure, psi	D747	100,000
Vicat Softening Temperature, °C	D1525	125
Hardness, Shore "D"	D2240	60
Environmental Stress Crack Resistance, hr/F_{50} **	D1693	> 1,200
Torsional Stiffness, psi	D1043	80,000
Low-Temperature Brittleness, °C/F_{50} **	D746	< − 76

*Density of the molded, crosslinked part
**F_{50} = 50% failure

TABLE 7-28

NOMINAL PHYSICAL PROPERTIES OF MARLEX® CL-100[34]

PROPERTY*	ASTM TEST	VALUE
Density, g/cm³ **	D1505-68	0.930-0.933
Environmental Stress Cracking Resistance, F_{50}, hr	D1693-70	> 1000
Tensile Strength, Ultimate, psi 2 in./min	D638-68 Type IV Specimen	2600
Elongation, At Break, % 2 in./min	D638-68 Type IV Specimen	450
Vicat Softening Temperature, °F	D1525-65T	~ 240
Brittleness Temperature, °F	D746-64T	< − 180
Flexural Modulus, psi	D790-66	100,000
Dielectric Strength 1/8 in. thick, V/mil	D149-64	475

*Physical properties are based on parts rotational molded with percent gel greater than 95%.
**Density of the crosslinked product.
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7-11.5 PROPERTIES

Typical properties of crosslinked polyethylene are shown in Tables 7-27 and 7-28.

7-12 POLYPROPYLENE

Present available polypropylene formulations lack adequate impact strength for rotationally molded parts. An inert gas atmosphere has given better properties with less degradation over a standard vented mold. Formulations specifically tailored for rotational molding to prevent oxidative degradation are required.

7-12.1 RAW MATERIAL PARAMETERS

The usual 35 mesh particle size is recommended. Fig. 7-12 presents a nomograph for determining the approximate charge weight of polypropylene for a given wall thickness.

Colored parts can be made by dry blending pigment with the natural polypropylene powder. For noncritical applications tumble blending of pigment is satisfactory. If extreme care in color-on-color uniformity is required, then blending in a high intensity mixer like a Henschel mill is recommended.

There are presently no suppliers of rotational molding powder but polypropylene pellets can be obtained from

1. Hercules Incorporated
   Wilmington, Delaware 19808

2. The Rexene Polymers Corp.
   115 W. Century
   Paramus, New Jersey 07652

3. Amoco Chemicals Corp.
   130 E. Randolph Drive
   Chicago, Illinois 60601

The cost is approximately $0.56 per lb.

7-12.2 PROCESS VARIABLES

7-12.2.1 Heating Cycle

It has been found with Pro-fax SB-351 that better moldings can be accomplished by dividing the heating cycle into two parts, an initial phase in which the molds remain motionless and a second phase in which the molds are rotated. The duration of the nonrotating dwell is dependent on mold dimensions and material but 3 to 4 min is a good starting point.

Typical start-up cycle conditions for rotational molding of a Pro-fax SB-351 polypropylene sphere with 1/8 in. wall thickness in a 1/4 in. thick aluminum mold are[27].

1. Mold rotation ratio: 2/1

2. Major axis setting: 10 rpm

3. Minor axis setting: 15 rpm

4. Forced air oven temperature: 710°F

5. Heating time: 3 min dwell, 7 min rotating

6. Cooling time (water mist spray): 4 min

Color has a definite effect on cycle times. Most cycle times must be increased to produce the desired consolidation and physical properties.

7-12.2.2 Cooling Cycle

Cooling is accomplished by water spray.

7-12.3 MOLD RELEASE AGENTS

Aluminum molds can be used without mold release when molding polypropylene. Only where other materials have stuck to the mold surface or impurities are present in the aluminum will sticking occur. If such areas
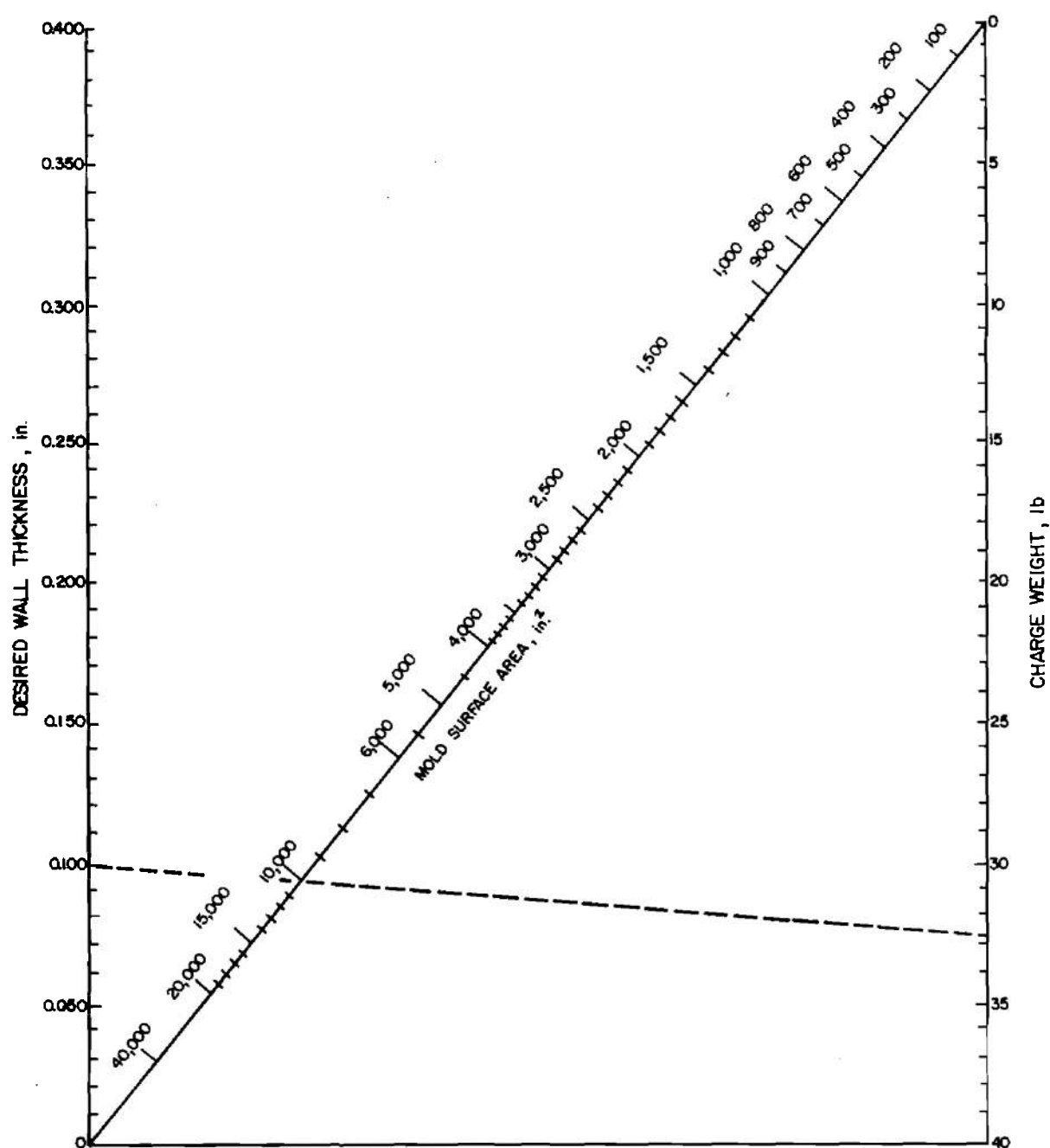
Figure 7-12. Nomograph for Determining the Approximate Charge Weight of Polypropylene for a Given Wall Thickness[27]

(Draw straight line through desired wall thickness and mold surface area to weight line and read weight.)

Example: A 0.100 in.-wall thickness on mold with 10,000 in.² area required 32.6 lb.

exist, they should be cleaned off or given a light coating of fluorocarbon mold release. In production it is only necessary to see that the mold is clean and dry before introducing the new charge of material.

Steel molds should be given an initial light coating of fluorocarbon mold release. Whenever a "sticking" condition develops, those areas affected should be recoated.

On molds where the parting line allows a large area of flash it is advisable to coat these flash areas intermittently with mold release. This makes cleaning of the mold between parts much easier[27].

7-12.4 EQUIPMENT

Where an existing mold is to be used, consideration must be given to the mold shrinkage of polypropylene which is approximately 0.015 in./in. This is roughly 1/2 that of the average low or high density polyethylene. Therefore, the polypropylene part will be somewhat larger than a polyethylene part produced in the same mold.

Molds should be provided with small vent tubes to allow escape of the internal gases during heating.

7-12.5 PROPERTIES

An indication of property data is given in Table 7-29 for injection molded general purpose sample.

7-13 POLYSTYRENE

Polystyrene is a rigid thermoplastic that gives a finished surface that is hard, yet is warm to the touch. Modified polystyrene is not waxy and can be nailed, stapled, cemented, and sawed. Because of these characteristics, products presently produced in wood can be developed in the modified plastic.

7-13.1 RAW MATERIAL PARAMETERS

Polystyrene has been rotomolded from a 35-mesh particle size powder and a spherical bead[29,30]. There is a definite limitation as to the depth of color which can be produced. However, a wide range of pastels is available[31].

At this writing there are no commercial suppliers of rotomolding grade polystyrene.

Pigments have been blended into polystyrene powder by stirring, ribbon blending, or tumbling. The following pigments have produced satisfactory dispersions without detrimental effect on moldability[30]:

Chromic Oxide Green G-6099—C. K. Williams & Co.

TiO_2—TiPure R-100—du Pont E. I., De Nemours & Co., Inc.

Pure Black Iron Oxide BK-247—C. K. Williams & Co.

Mercadmium Red Medium Conc. X-2570—Hercules Powder Co., Inc.

C.P. Deep Orange A-4337—Hercules Powder Co., Inc.

Mapico Lemon Yellow—Columbian Carbon Co.

Monastral Blue B+449D—du Pont E. I., De Nemours & Co., Inc.

7-13.2 PROCESS VARIABLES

7-13.2.1 Heating Cycle

Normal oven temperatures for polystyrene range from 450° to 900°F. Most rotational molding is carried out at oven times of 6 to 12 min[29]. A typical oven cycle for a large

TABLE 7-29

PROPERTIES OF PROFAX 6323, 6523 POLYPROPYLENE[28]

PROPERTY	TEST METHOD	TYPE 6323	TYPE 6523
Density, g/cm^3	D792A-2	0.904	0.904
Izod Impact at 23°C, ft-lb in. notch (1/8-in. specimen)	D256A	0.4	0.5
Izod Impact at −18°C, ft-lb in. notch (1/8-in. specimen)	D256A	0.3	0.3
Tensile Strength at Yield, psi (1/8-in. Type III specimen)	D628 2 in./min	5,000	4,900
Flexural Modulus (1% secant), psi (1/8-in. specimen)	D790B 2-in. span	230,000	220,000
Stiffness in Flexure, psi (1/8-in. specimen)	D747 4-in. span	160,000	155,000
Rockwell Hardness, R Scale	D785A	99	99
Deflection Temperature at 66 psi, °C (1/8-in. specimen)	D648	101	99
Deflection Temperature at 264 psi, °C (1/8-in. specimen)	D648	59	59
Deformation Under Load 1,000 psi and 50°C, % (composite of 1/8-in. specimens)	D621A	1.3	1.3
Deformation Under Load 2,000 psi and 50°C, % (composite of 1/8-in. specimens)	D621A	5	5
Water Absorption, 24 hr, %	D570	0.02	0.02
Environmental Stress Cracking	D1603	Does not	Does not
Coefficient of Linear Thermal Expansion, in./in.-°C (Annealed specimen)	D696		
−30° to 0°C		6.4×10^{-5}	7.1×10^{-5}
0° to 30°C		8.6×10^{-5}	9.7×10^{-5}
30° to 60°C		9.4×10^{-5}	11.0×10^{-5}
Shrinkage From Mold Dimension, in./in. (parallel to flow, 1/8-in. specimen)	D955	0.015	0.015
Shrinkage From Mold Dimension, in./in. (parallel to flow, 1/16-in. specimen)	D955	0.009	0.009

All molded specimens prepared by injection molding (ASTM-D2146).

hollow high impact polystyrene part would be 720°F for approximately 10 min[31].

Typical molding cycles will vary with mold composition and wall thickness, oven temperature, and wall thickness of the part. Some examples of molding cycles are cited in Table 7-30 with polystyrene powder[30]. These examples are to be used only as guides since oven heat capacity and air velocity, in addition to the previously mentioned variables, will determine actual cycle times required. Venting of the mold sometimes is recommended to ensure optimum uniformity of wall thickness when molding in large volume molds.

TABLE 7-30

EXAMPLES OF MOLDING CYCLES WITH POLYSTYRENE POWDER[30]

MOLD				PART		OVEN	
COMPOSITION	THICK, in.	SIZE, in.	SHAPE	WT, g	THICK, in.	TEMP, °F	TIME, min
Stainless Steel	0.035	7.25 (Dia) X 8.5	Cylindrical	600	0.125	450	20
Stainless Steel	0.035	7.25 (Dia) X 8.5	Cylindrical	600	0.125	550	10
Stainless Steel	0.035	7.25 (Dia) X 8.5	Cylindrical	1200	0.250	550	15
Sheet Metal	0.0625	14 X 13.5 X 6	Rectangular	1400	0.125	550	10
Sheet Metal	0.0625	14 X 13.5 X 6	Rectangular	2800	0.250	550	15
Aluminum	0.250	5 (Dia)	Spherical	180	0.125	550	10
Aluminum	0.250	5 (Dia)	Spherical	360	0.250	550	15

Length-to-diameter ratios must be limited because of "bridging". A 4:1 L/D ratio is considered to be a maximum as a general rule[31].

7-13.2.2 Cooling Cycle

Cooling usually is accomplished by water spray during rotation. Care should be taken to prevent too rapid a cooling rate. This can be controlled by regulating the flow of water, the temperature of the water, or by mixing air cooling with water cooling.

7-13.3 MOLD RELEASE AGENTS

The use of mold release agents is not required with polystyrene powders. Difficulty may occur in molds having insufficient draft, due to the small amount of shrinkage. A light application of a silicone release agent may be of assistance in such instances.

TABLE 7-31

PROPERTIES OF POLYSTYRENE[30]

Bulk Density, g/cm^3	0.48
lb/ft^3	30
Specific Gravity	1.04
Izod Impact, ft-lb/in. of notch, 90-mil specimen	0.5
Falling Weight Impact[1], ft-lb,	
150-mil specimen	1
200-mil specimen	2.5
Tensile Strength, psi	3,000
Flexural Yield, psi	5,500
Flexural Modulus, psi,	
74°F	411,000
120°F	324,000
140°F	220,000
160°F	84,000
Durometer Hardness, Shore "D"	75
Heat Distortion Temperature, 264 psi, °F	162
Vicat Softening Point, °F	176
Shrinkage[2], in./in.	0.002-0.007

Note: (1) Two pound weight having 5/8 in. dia punch
(2) Shrinkage is dependent on specimen geometry

7-13.4 EQUIPMENT

Due to the low shrinkage factor for polystyrene, a draft angle must be provided in the mold design. Also, undercuts should be eliminated. Mold detail is reproduced extremely well, and a highly polished mold is essential for a glossy surface.

7-13.5 PROPERTIES

Table 7-31 presents some typical properties of natural polystyrene rotational molding powder.

7-14. POLYVINYL CHLORIDE (PVC)

Powders suitable for rigid or semirigid rotational molding require further development for adequate flow and stability. At present there are no commercial suppliers of rigid PVC powders.

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CHAPTER 8

ADVANTAGES AND DISADVANTAGES OF ROTATIONAL MOLDING

8-1 GENERAL

Rotational molding not only broadens the limits of part design but also has many advantages when compared with other molding techniques. Some of the advantages are listed in par. 8-2.

8-2 ADVANTAGES

Some advantages of rotational molding follow:

1. The lead time for tooling is much shorter than other processes.

2. Costs for molds and tooling are low, especially for short runs. The technique, however, can be adapted easily to continuous production methods and high production rates when multiple molds are used.

3. Prototype molds can be manufactured for experimental purposes without great exposure.

4. This process permits a wider selection of mold materials than most other processes. Copper, Be/Cu, stainless steel, carbon steel, aluminum, nickel, and combinations of these have all been used successfully.

5. There is little or no waste scrap since the desired weight of the part is placed into the mold.

6. Parts having complex shapes, convoluted wall sections, undercuts, and large surface areas can be molded easily.

7. Part sizes are limited only to oven size and strength of the mold spindles.

8. Cross-sectional part deformation and warpage are at a minimum.

9. Wall thickness can be closely controlled and uniform.

10. Parts can be made seamless and relatively stress-free with a minimum of locked-in stresses. This latter asset permits superior environmental stress-crack resistance.

11. Identical, similar items, or different sections of one piece can be molded at the same time in different colors on a single spindle.

12. Plastic or metal inserts can often be molded as integral parts of the item.

13. Double-wall, composite, glass reinforced, and foamed constructions are feasible.

14. Excellent detail and finish, various textures, or high gloss can be obtained on exterior surfaces.

8-3 DISADVANTAGES

Some disadvantages of rotational molding follow:

1. The main disadvantage is the limited range of commercially suitable materials for this process. Also, there is the additional cost of the material since the powder must be ground from conventional extrusion pellets.

2. For the most part, molds must be manually loaded and unloaded. Automatic part ejectors have not proved practical owing to the high environmental temperature, thermal cycling, and the complex mechanism

of the rotating assembly. Mechanical robots are futuristic. Thus, labor per piece remains high, limiting the process application. In addition, the manual loading and unloading contribute to a longer molding cycle than injection and blow molding.

8-4 COMPARISON OF PROCESS CHARAC-TERISTICS

Fig. 8-1 compares the major molding process characteristics.

MOLDING METHOD	ABILITY TO MOLD PARTS GREATER THAN 4 ft LONG	LOW MOLD COST	LOW COST FOR LARGE PARTS	ABILITY TO MOLD DOUBLE WALL CNTNR	ABILITY TO MOLD INSERTS	MATERIAL VARIETY AVAILABLE	ABILITY TO MOLD THERMO-SETS AND THERMO-PLASTICS
ROTATIONAL	EXCELLENT	GOOD	EXCELLENT	EXCELLENT	GOOD	FAIR	FAIR
BLOW	GOOD	GOOD	GOOD	GOOD	POOR	GOOD	POOR
INJECTION	GOOD	FAIR	GOOD	POOR	GOOD	EXCELLENT	FAIR
VACUUM	EXCELLENT	EXCELLENT	EXCELLENT	FAIR	POOR	EXCELLENT	POOR

KEY:

█ EXCELLENT   ▨ GOOD   ▧ FAIR   ☐ POOR

Figure 8-1. Process Characteristics

CHAPTER 9

ECONOMICS

9-1 GENERAL

Very few cost comparisons have been made between the various processes. This is primarily due to the fact that the process selection normally depends on the part design and the polymer selected. As noted under the materials chapter, not all resins are suitable for rotational molding. In fact of all the resins available, the powders recommended for rotational molding are very limited, especially in the so-called "engineering plastics" area.

Also, the same resin system cannot be used in different processes. With rotational molding, for example, a change in resin composition, density, melt index, or molecular weight makes a much larger change in cycle time than it does with injection or blow molding. However, some basic economic statements can be made for the rotational molding process.

9-2 ECONOMIC CONSIDERATIONS

Some economic considerations of rotational molding follow:

1. Rotational mold costs are relatively low in comparison with injection and blow molding. This is because the internal pressures developed inside the mold are in the order of 0.25 to 1.5 psi and only female molds are used. Generally, there is a savings of approximately 80 percent. Tool delivery is much faster, around 6 to 8 weeks compared to 14 to 18 weeks for injection molds.

2. Since the cost of rotational molds is rather low, the molder can modify the molds if necessary. Prototype items can be produced readily. Also, different molds of similar size can be run on the same spider so that little production time on other items is lost.

3. Changes in wall thicknesses do not require tooling changes but only quantity of molding powder and cycle time.

4. There also is the ability to mold items of different colors at one time on a single spindle or single machine.

5. Multilayer items can be molded with different materials or different colors or both in one mold; for example, a polyethylene-lined nylon container.

6. There is very little scrap or waste material and trimming compared to injection and blow molding.

7. Usually the larger the item, the more economical rotational molding becomes over other processes.

8. High production rotational molding facilities require considerably more space than other processes. Excluding office space, generally, four to five times the floor space of the rotomolding machine is required. In addition, the facility should be equipped with concrete floors, 13- to 20-ft ceilings, exhaust stacks, and fuel source such as natural gas, propane, or oil for ovens, all of which are not required in blow and injection molding facilities[2].

9. Many large volume molders have found it economical to purchase grinding equipment and to grind the pelletized material in their plants. It is estimated that a savings of approximately $0.05 per lb can be realized[2].

TABLE 9-1

SELECTED POLYETHYLENE ITEMS

ITEMS	WALL THICKNESS, mil	5.0 MELT INDEX PE INJECTION, ROTA- TIONAL MOLDING WEIGHT, lb	1.0 MELT INDEX PE BLOW MOLDING WEIGHT, lb
20-gal waste can with lid	90	5.35	5.89
55-gal drum with lid	90	9.5	10.5
250-gal tote bin	200	48.7	53.6

9-3 ECONOMIC STUDY

A study compiled by Arthur D. Little, Inc., for U.S. Industrial Chemical Company, compares containers of various sizes by injection molding, rotational molding, and blow molding[1]. The highlights are presented here to illustrate the possible economics involved in the different processes. The containers are described in Table 9-1.

The following assumptions were made in this study:

1. A good molder with economical equipment; a trained work force; and a location with moderate labor and utility costs were utilized.

2. A five year write-off on the plant, a two year write-off on molds, and a ten percent return on investment were assumed.

3. Where production is less than plant capacity, the investment write-off, except for the molds, was prorated on an hourly basis. The molds were written off on the length of run.

4. All parts in the study were compared on the basis of equal strength. This is quite important because, in the blow molding process, much of the plastic remains in relatively thick sections of the bottom and top pinch points and not in the wall. Thus, in parts of equal minimum wall thickness, the blow molded item may weigh thirty to one hundred percent more than the injection or rotationally molded items. The weight of a

blow molded article may be reduced by programmed parison control but only at some cost in cycle time[1].

5. Variations in wall thickness in blow molding are partially compensated by the higher viscosity resins. This study assumed that the blow molded items weighed about ten percent more than comparable injection or rotationally molded parts.

6. To make a fair comparison between processes, cycles and production levels were selected to represent the best average levels a typical molder without specially engineered facilities could expect to meet.

7. The quantities considered were ten thousand to ten million items per year. The unit costs are shown in Figs. 9-1 through 9-3.

Fig. 9-1 shows the costs of the 20-gal container. Injection molding is the most economical means of making this item except at low production levels.

Fig. 9-2 shows the rotational molding
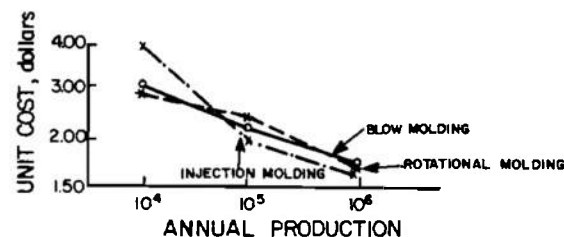
Figure 9-1. Comparative Unit Costs, 20-gal Container[1]
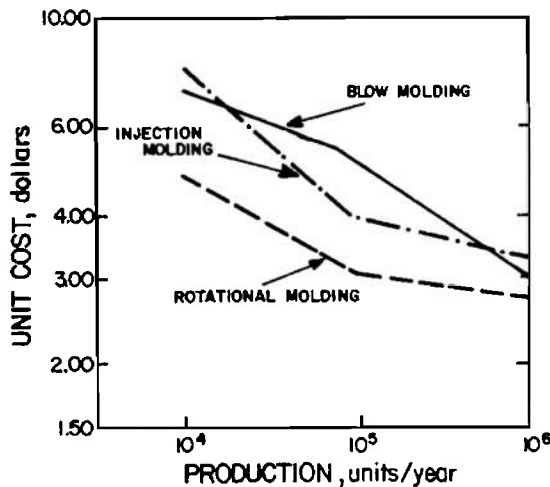
Figure 9-2. Comparative Unit Costs,
55-gal Container[1]

Figure 9-3. Comparative Unit Costs,
250-gal Container[1]

process as the most economical way of making the 55-gal container. Some 55-gal drums are being made by injection and blow molding in spite of high cost. These are usually made at fairly high production rates where the costs are not as critical, and usually they are being made with resins such as high-density or high-viscosity polyethylene which require long rotational cycles or are not suited to rotational casting[1].

Fig. 9-3 shows the unit cost for the 250-gal tote bin. Again, rotational casting has the lowest cost at all levels. Injection molding approaches fairly close to it. Even though low production costs are quite high, unit cost drops rapidly. Blow molding costs most at high quantities. There is some doubt on an item this large — this weighs 50 lb — whether it can be blow molded.

As revealed by these figures, production rates can have a larger effect on the cost of the item than the method of production. This is because the mold investment costs play a large role in the costs at lower production levels and the poorer overall efficiencies

experienced at low production levels.

Blow molding unit cost decreases rapidly and levels out. Rotational molding unit cost starts lower than the blow molding, and with high production equipment drops considerably. Injection mold cost and high investment make it very costly for low production items. With higher production, the unit cost decreases in the same general region as blow molding and rotational molding.

Therefore, even at the lowest production levels, it is apparent that rotational molding has the lowest unit cost per container no matter which item is chosen, while injection molding has the highest costs. Thus, the rotational molding process with conventional hot air machine, the short run and prototype moldings, is economically superior to injection or blow molding.

Table 9-2 offers some representative cost of operating conventional hot air rotating machines. These are machine costs only and do not reflect labor, facility, resin, and mold costs.

TABLE 9-2

REPRESENTATIVE COSTS
OF OPERATION OF
HOT AIR ROTATING MACHINES[2]

(1) HEAT

Lb Capacity/ Arm	In. Spherical Dia Swing	Hourly Cost
500	48	$0.25
800	64	$0.40
1500	88	$0.60
1700	110	$0.80
3000	200	$1.25
5000	204	$1.60

Based on average price of gas at 70¢/1000 ft^3. Oven consumption at 1000 ft^3/hr or each 1,000,000 Btu of oven output. Average oven usage: 60%.

(2) ELECTRICITY

500	48	$0.09
800	64	$0.14
1500	88	$0.22
1700	110	$0.31
3000	200	$0.56
5000	204	$0.65

Based on 15¢/kW-hr and average usage or efficiency of 50%.

Lb Capacity/ Arm	In. Spherical Dia Swing	Hourly Cost
(3) WATER		
500	48	$0.04
800	64	$0.10
1500	88	$0.15
1700	110	$0.75
3000	200	$0.75
5000	204	$1.00

Based on 50¢/100 ft^3. Water consumption is approximately 4, 5, 12, 30, 40 and 50 gal/min for the 6 basic models at continuous water usage. Water recirculation reduction is 50-75% depending on cycle. Water usage, however, is only about 50%, resulting in the given costs.

(4) DEPRECIATION

500	48	$0.30
800	64	$0.60
1500	88	$0.96
1700	110	$1.50
3000	200	$2.60
5000	204	$3.00

Assumes 10-year depreciable life at 5 days/wk round-the-clock operation and 80% load factor.

(5) TOTAL COST OF OPERATION

500	48	$0.68
800	64	$1.24
1500	88	$1.93
1700	110	$3.36
3000	200	$4.16
5000	204	$6.25

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CHAPTER 10

APPLICATIONS

10-1 GENERAL

Rotational molding is not a replacement of either injection or blow molding, but is another process that is designed to produce items of design features which limit other processes either physically or economically. For example, injection molding produces high precision parts at high production rates, but is not feasible for a one-piece closed vessel. Blow molding is best suited for making bottles and other items which have reentrant curves that require a high-viscosity resin. It is not well-suited to making heavy-walled parts. Rotational molding is best suited to making closed parts with heavy walls.

Rotational molding also is well suited for small quantities of large items for which mold costs are an important factor, or in the development of a new item in which changes must be made quickly and inexpensively and various wall thicknesses must be tried. This technique produces parts of uniform thickness and without the internal stresses that thermoforming might produce. It is generally used for large parts such as drums and carboys. The minimum wall thickness that can be produced is about 0.030 in.

There are virtually no limitations to the hollow shapes that can be molded. Products may be made seamless and strain free. Also, intimate detail, various textures, or high glosses are obtained easily. Commercial applications utilizing rotational molding are listed in the paragraphs that follow.

10-2 MARINE APPLICATIONS

Marine applications include:

1. Marker buoys

2. Boat bumpers

3. Rafts, floats

4. Boat hulls

5. Holding tanks

6. Gas tanks

7. Surfboards

8. Aquariums.

10-3 PACKAGING APPLICATIONS

Packaging applications include:

1. Luggage

2. Trash containers

3. Tote boxes

4. Shipping igloos for aircraft

5. Containerization for ships, rail, and trucks

6. Shipping drums.

10-4 AUTOMOTIVE APPLICATIONS

Automotive applications include:

1. Traffic cones

2. Air ducts

3. Fuel tanks

4. Glove compartments

5. Camper bodies

6. Fender liners

7. Dashboards

8. Auto bodies

9. Battery cases.

10-5 TOYS

Toy applications include:

1. Hobby horses

2. Dolls

3. Basket balls

4. Volley balls.

10-6 APPLIANCES

Applicance applications include:

1. Humidifiers

2. Ducts for refrigerators and freezers

3. Ice chests

4. Lamps

5. Housings for business machines, vending machines.

10-7 TANKS

Tank applications include:

1. Water

2. Milk

· 3. Waste receptacles

4. Agricultural-chemical

5. Truck

6. Holding for trailers, boats

7. Gasoline for lawn mowers, snow-mobiles, etc.

10-8 RESIDENTIAL APPLICATIONS

Residential applications include:

1. Garden planters

2. Furniture—tables, cabinets, chairs, etc.

3. Lamp globes

4. Mail boxes

5. Water closets

6. Sinks and shower stalls.

10-9 MILITARY APPLICATIONS

Military applications include:

1. Aircraft flight simulator

2. Bomb case

3. Bomb dispenser

4. Missile containers.

10-10 MISCELLANEOUS

Miscellaneous applications include:

1. Burial vaults

2. Light globes

3. Portable outdoor toilets

4. Mannequins

5. Pipe

6. Medical equipment: urinal, emesis basins.

GLOSSARY*

alloy. Various polymers or copolymers blended or mixed to develop a material of certain desired properties.

ambient temperature. The temperature of the medium surrounding an object.

amorphous. Noncrystalline; without descriptive physical form or selective structure.

annealing. A process of using time and a temperature below the melting point of a material to relieve stresses and strains that may be introduced during a molding operation.

antioxidant. Substance that, when added in small quantity to the resin during the mixing, prevents its degradation and contributes to the maintenance of its properties.

arm. That portion of the rotating molding machine containing the required drive engines, shafts, and gears necessary to produce simultaneous rotation about two axes that are at right angles to each other (also called spindle).

backing plate. Sometimes referred to as a support plate. This is a plate used to back up cavity blocks, inserts, and pins.

Biot number. Ratio of heat transfer resistance in convective film of fluid next to the mold surface to the resistance to conduction heat transfer within the mold material.

blister. An imperfection on the surface of the molded article caused by gases, trapped within the part, that were given off during the molding operations.

blowing agents. Chemicals added to plastics

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*See also: ASTM D883-72c, *Definition of Terms Relating to Plastics*.

that generate inert gases on heating, causing the product to assume a cellular structure.

blow molding. A process by which a tube (parison) of softened plastic is formed into the shape of the mold cavity by blowing air under pressure through the tube.

boss. A protrusion, land, or bump on a part. A boss is used for such functions as locating, fastening, or adding strength.

bubble. A spherical, internal void; globule of air or other gas trapped within a plastic.

bulk density. The density of a molding material in loose form expressed as a ratio of weight to volume.

bulk factor. The ratio of the volume of loose molding powder to the volume of the same weight of the part molded from this material.

cast. To pour a liquid plastic material into a mold and allow it to harden or "polymerize".

cavity. A depression in a mold that forms the external surfaces of a plastic part.

cellular plastic. A plastic whose density is decreased substantially by the presence of numerous cells disposed throughout its mass.

centrifugal casting. Centrifugal or rotational casting is a molding operation in which a plastic material is placed in a mold that can be rotated on several axes. The rotating action, coupled with a heating and cooling operation, permits the plastic to melt and then harden into the desired shape against the walls of the mold.

charge. The measurement or weight of material used to load a mold at one time or during one cycle.

clamping pressure. The pressure required during the molding operation to keep the mold closed against the pressure of the material.

coefficient of linear expansion. A measure of the change in dimension of an object caused by a change in temperature; specifically measured by the increase in length of an object per unit length per degree change in temperature.

coefficient of thermal expansion. The change in volume per unit volume produced by a one degree rise in temperature.

cold flow. *See:* creep.

conditioning. Treating test specimens or parts so that they are uniform before tests or processes are performed on them. This allows the results to be comparable to each other.

copolymer. A polymeric system which contains two monomeric units.

crazing. A network of fine cracks on or under the surface of a plastic part; can be induced by testing with certain solvents.

creep. Sometimes called "cold flow". This is the dimension change in a plastic under continuous load.

crosslinking. The setting up of chemical links between the molecular polymer chains. When extensive, as in most thermosetting resins, crosslinking makes one infusible super-molecule of all the chains.

crystallinity. A state of molecular structure in some resins attributed to the existence of solid crystals with a definite geometric form. Such structures are characterized by uniformity and compactness.

cure. Commonly applied to the chemical change a thermoset material goes through, under heat and pressure, during the molding process.

cycle. The cycle or cycle time of a molding operation is considered from one point to the corresponding point in the next repeated sequence.

deflashing. Covers the complete range of operations used to remove the flash from a molded plastic part.

degradation. A deleterious change in the chemical structure of a plastic.

density. The weight per unit volume.

deterioration. A permanent change in the physical properties of a plastic as evidenced by impairment of these properties.

dimensional stability. A property of the material to hold its exact shape after it has been molded. Dimensional stability can be correlated to shrink factor and other material properties.

discoloration. A change from an original color in a material; caused by such things as degrading the material by overheating, chemical attack, or exposure to sunlight.

draft. The amount of taper given to the side walls of a molded part to allow for easier removal from the mold.

dry-blend. A free-flowing dry compound prepared without fluxing or addition of solvents.

dry coloring. A method of mixing dyes and pigments with uncolored plastics to produce a desired color of the part.

electroformed mold. A mold made by electroplating a metal onto a reverse image of the part to be molded.

embossing. A process used to produce depressions on a plastic sheet or part.

environmental stress cracking. The cracking or crazing of a plastic material subjected to a

combination of chemical and stress.

filler. A cheap, inert substance added to a plastic to make it less costly. Fillers may also improve physical properties, particularly hardness, stiffness, and impact strength. The particles are usually small.

finish. The ultimate surface appearance of a plastic part.

flash. Excess plastic on a molded part found at the mold parting line, or in cavity areas that are worn, inverted, or loose.

flash line. A raised line similar to a parting line on the face of a molded part. It is caused by the match line of the opposite molding surface.

foamed plastics. Plastic resins with a sponge-like structure. They can be rigid or nonrigid, open or closed cell, and of various densities.

foaming agents. Chemicals added to plastics to produce a gas that causes foaming action and foams the cellular structure.

fusion. In vinyl dispersions, the heating of a dispersion to produce a homogeneous mixture. There is an apparent mutual solvation of the resin and plasticizer.

gloss. The shine or luster of a surface.

grit blasted. A method of "roughing up" the cavity surface, and also a means of removing flash from a molded part. In the case of the cavity, sand or steel shot usually is used. For flash removal, sand or finely ground nut pits are used.

heat sink. A contrivance for the absorption or transfer of heat away from a critical element or part.

hob. A hardened steel pattern used to sink that shape into soft steel to form a mold cavity.

hobbing. The method of forming cavities in a mold by pressing the hob into the steel under high pressure.

homopolymer. A polymer consisting of only one monomeric species.

hopper dryer. A circulating hot air device used with a hopper to keep the plastic material dry.

injection molding. The method of forming objects from granular or powdered plastics, most often of the thermoplastic type, in which the material is fed from a hopper to a heated chamber in which it is softened, after which a ram or screw forces the material into a mold. Pressure is maintained until the mass has hardened sufficiently for removal from the mold. In a variation called flow molding additional molten material is forced into the mold during cooling of the initial charge to overcome shrinkage. When a screw is used rather than a ram for applying injection pressure by forward movement of the screw, the term reciprocating screw injection molding is applied. In another variation called the screw-piston type of injection molding, the screw does not reciprocate but delivers the molten material to an accumulator chamber through a check valve, then a piston forces the material from the chamber into the mold.

insert. A component (usually metallic) either molded in, or pressed into, a plastic part. Sometimes a separate piece or section of a mold is called an insert.

laminar flow. The movement of one layer of fluid past another layer with no transfer of matter from one to the other. The friction between two such layers is called viscosity coefficient. Laminar flow of thermoplastic resins in a mold is achieved by solidification of the layer in contact with the mold surface, thus providing an insulating tube through which material flows to fill the remainder of the cavity. This type of flow is essential in order to duplicate the mold surface.

major axis. By choice, the axis parallel to the ground.

melt index (MI). A measurement of thermoplastic material viscosity.

micron. A unit of length, 1×10^{-6} m; 0.001 mm; 10^4 Angstroms; or about 0.00004 in.

minor axis. By choice the minor axis is the moving axis. Its relationship to ground is continuously changing during operation, but it is always normal to the major axis.

moisture absorption. The pick-up of water vapor from air by a material.

mold. The tool used to produce the shape of a plastic part.

molding cycle. The time required to produce a plastic part in a molding operation. Measured from a point of one operation to the same point of the first repeat of the operation.

molding powder. Plastic molding compound in a powder form (as opposed to granular form).

molding shrinkage. The difference in size, expressed in inches per inch, between the plastic part and the mold cavity, both being at room temperature when measured and usually 24 hr after molding.

mold release. A lubricant such as wax, powder, or spray used to coat the cavities of a mold to prevent the part sticking or hanging up in the mold, and allowing for easy ejection.

monomer. A relatively simple compound which can react to form a polymer.

multicavity mold. A mold that produces more than one plastic unit.

Newtonian liquid. A liquid in which the rate of flow is directly proportional to the force

applied. The viscosity is independent of the rate of shear.

parison. In blow molding, the hollow plastic tube from which a product is blown.

parting line. A mark on a plastic molding caused by the meeting of the mold halves.

plasticizer. Chemical agents added to plastic compositions to improve flow and processability, and to reduce brittleness. This is achieved by lowering the glass transition temperature.

pock-marks. Slight indentions that sometimes occur on the surface of the crosslinked part. They are generally round and vary in size from about 0.75 in. to 1.5 in. in diameter and a depth between 0.005 in. to 0.030 in.

polymer. Compound formed by the reaction of simple molecules having functional groups that permit their combination to proceed to high molecular weights under suitable conditions. Polymers may be formed by polymerization (addition polymer) or polycondensation (condensation polymer). When two or more monomers are involved, the product is called a copolymer.

porous molds. Molds which are made up of bonded or fused aggregates (powdered metal, coarse pellets, etc.) in such a manner that the resulting mass contains numerous open interstices of regular or irregular size.

powder molding. A general term encompassing rotational molding, slush molding, and centrifugal molding of dry, sinterable powders such as polyethylene, nylon, and PVC. The powders are charged into molds that are heated and manipulated according to the process being used, causing the powders to sinter or fuse into a uniform layer against the internal mold wall.

powdered plastics. Resins or plastic compounds which have been finely pulverized for use in fluidized bed coating, rotational

molding, and various sintering techniques.

powder thermal diffusivity. The thermal conductivity divided by the product of the density and the specific heat.

predrying. The drying of a resin or molding compound prior to its introduction into a mold. Some plastic compounds are hygroscopic and require this treatment, particularly after storage in a humid atmosphere.

prototype mold. Usually an inexpensive mold constructed of soft metals or epoxies or combination of same. Used for development of permanent tooling (molds), final part design, final process determination, and for short-run model parts.

PVC. Polyvinyl chloride.

release agent. A lubricant used to coat the cavities of a mold to allow for easier release or ejection of the part from the cavity without sticking.

resin. Any of a class of solid or semi-solid organic products of natural or synthetic origin, generally of high molecular weight, with no definite melting point. Most resins are polymers (*qv*).

rib. A reinforcement to a plastic part to add functional strength.

rotational casting. Also called rotational molding; a process used to mold hollow parts, usually of a large size. The material is placed in the cavity of a mold that rotates on two axes. The mold is subjected to alternate heating and cooling while rotating and the material melts and adheres to the cavity walls to form the shape desired.

rotational ratio. This is the ratio of major axis rpm to minor axis rpm, and more specifically the ratio R when both numerator and denominator are reduced to the lowest possible whole numbers by multiplying both by the same quantity.

rotomolding. A contraction of the term rotational molding. *See also:* rotational casting, powder molding, slush molding.

set. Interchangeable term with cure; to allow the plastics to change from liquid to solid.

slush casting. A method of forming hollow objects, widely used for doll parts and squeeze toys, in which a fluid plastic mixture, usually vinyl plastisol, is poured into a hollow mold provided with an opening until the mold is full. Heat, applied to the mold before and/or after filling, causes a layer of material to gel against the inner mold wall. After the layer has reached the desired thickness, the excess fluid material is poured out, and additional heat is applied to fuse the layer. After cooling, the article is stripped from the mold. Molds for slush casting are thin-walled for rapid heat transfer. Electroformed copper molds or aluminum castings are used most often.

slush molding. The preferred term for the process similar to slush casting but employing dry, sinterable powders.

spider. Matching sets of metal frame work which have the mating halves of molds affixed to them. Mold halves are clamped together by clamping the "spiders" together, not the individual molds.

spindle. *See:* arm.

stabilizer. An ingredient used in the formulation of some polymers to assist in maintaining the physical and chemical properties of the compounded materials at their initial values throughout the processing and service life of the material, e.g., heat and UV stabilizers.

thermal conductivity. The ability of material to conduct or transfer heat. The physical constant for quantity of heat that passes through unit cube of a substance in unit time when the difference in temperature of two faces is 1 deg.

thermal decomposition. Decomposition resulting from action by heat. It occurs at a temperature for which some components of the material are separating or associating together, with a modification of the macro- or microstructure.

thermal expansion. The dimension change per unit length for each unit change in temperature.

thermal stress cracking. A cracking or crazing condition on the surface of a plastic part induced by overexposure to elevated temperatures.

thermoplastic. A thermoplastic is a material that goes through a physical change only under the application of heat and pressure. The material can be remelted and rehardened. Wax would be an example of the thermoplastic concept.

thermoset. A material that undergoes a chemical reaction by the application of heat and pressure. The material is softened, formed, and hardened. It cannot be remelted and rehardened.

trim. To remove flash or sharp edges and corners mechanically or by hand from a molding.

vent. Minute opening in the cavity of a mold to allow for escapement of trapped gases released during the molding cycle.

viscosity, dynamic. A measure of the internal friction resulting when one layer of fluid is caused to move in relationship to another layer. The units of measure are (1) the poise (shear stress in dynes per cm^2 divided by the rate of shear in seconds); (2) the centipoise (one one-hundredth of a poise); (3) the stroke, an expression of kinematic viscosity, (viscosity in poises divided by the fluid density, i.e., units of cm^2 per sec); and (4) the centistoke (one one-hundredth of a stoke).

The following table of approximate viscosities in centipoises at room temperature is useful for rough comparisons.

water	1
kerosene	10
motor oil, SAE 10	100
castor oil, glycerine	1,000
corn syrup	10,000
molasses	100,000

When the ratio of shearing stress to the rate of shear is constant, as is the case with water and thin motor oils, the fluid is called a *Newtonian* fluid. In the case of non-Newtonian fluids, the ratio varies with the shearing stress, and viscosities of such fluids are called apparent viscosities.

viscosity coefficient. The shearing stress necessary to induce a unit velocity flow gradient in a material. *Note:* In actual measurement, the viscosity coefficient of a material is obtained from the ratio of shearing stress to shearing rate. This assumes the ratio to be constant and independent of the shearing stress, a condition which is satisfied only by Newtonian fluids. Consequently, in all other cases, values obtained are apparent and represent one point on the flow curve. In the metric system, the viscosity coefficient is expressed in poises, units being dyne-sec per cm^2.

viscous flow. A type of fluid movement in which all particles of the fluid flow in a straight line parallel to the axis of a containing pipe or channel, with little or no mixing or turbidity.

voids. Gaseous pockets that have been trapped and cured into a laminate or molding; an unfilled space in a cellular plastic substantially larger than the characteristic individual cells.

warpage. Distortion in a plastic part after the molding operation.

weld line. Sometimes called a knit line or flow line. A visible line on the surface of a plastic part caused by the interruption of the flow of material or incomplete fusion of the material when joining.

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